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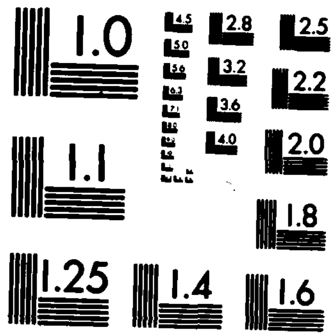

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THE EFFECT OF TURBULENCE ON THE ATMOSPHERIC TRANSMITTANCE

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This report describes the effect of turbulence on the atmospheric transmittance. The fluctuation of transmittance due to turbulence is incorporated into the Lowtran computer code in terms of two subroutines for plane wave sources and beam wave sources (including spherical wave sources), respectively. These two subroutines calculate the intensity and power scintillation index. The square root of these indices is then used to define the upper and lower bounds of transmittance deviation. The calculations are for point receivers as well as for finite aperture receivers which exhibit the aperture averaging effect.

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Final Report

Contents

A1

I. Introduction

An electromagnetic wave propagating through the earth's atmosphere is subject to attenuation due to scattering by molecules, aerosols and turbulence (which acts like a source of inhomogeneities) as well as due to absorption of radiation by atmospheric constituents in the atmosphere. In addition to attenuation, scattering by turbulence, in which the refractive index varies through space and time, makes the wave intensity fluctuate, especially for waves with wavelength shorter than millimeters. Because the wavefront is spread by the smaller scales and wandered by the larger scales of the turbulence, the reformed wavefronts cause the scintillation of the wave intensity.

In this report, we review theoretically the attenuation and fluctuation of the wave propagating through turbulent atmosphere and incorporate the results into the Lowtran[1] computer code in terms of two new subroutines. These added subroutines are used to calculate the normalized intensity (or power) variance, by which we define the upper and lower bounds of atmospheric transmittance. Since the wave attenuation due to turbulence, which will be discussed in section II, is not significant, we do not incorporate it into the calculation of atmospheric transmittance in Lowtran in which the attenuation due to molecular and aerosol's absorption and scattering is taken into account.

In practical systems, transmitters and receivers with finite apertures are used. A larger receiver aperture not only collects more power, but also reduces wave fluctuation. This is called the receiver aperture averaging effect. Also, a more coherent source gives rise to

smaller scintillations. Hence, the effects of aperture size, source coherence and turbulence on wave scintillation are included in the formulation[2] which will be used to code the new subroutines in Lowtran.

We have chosen pair-correlated field statistics[3], which act like Gaussian field statistics, to model the coherence poperties of sources. It is shown that these statistics yield satisfactory results[4].

The extended Huygens-Fresnel method[5] has been used to obtain scintillation expressions for partially coherent beam waves as well as for spherical waves. Since the wave structure functions which are used are valid for aperture sizes which are smaller than the Fresnel zone and since the parallel approximation is applied in the Huygens-Fresnel formulation, we cannot extend the beam wave result to the plane wave case simply by letting transmitter size go to infinity. Therefore, we derive the intensity variance for plane wave sources by use of the log-amplitude variance which can be obtained by Rytov's method[6]. Thus, two subroutines, VRANI and SINTL, are coded separately for plane waves and beam waves (including spherical waves), respectively.

II. Transmittance attenuation due to turbulence

The transmittance for a wave propagating through the atmosphere is defined as

$$\tau = \frac{\langle I \rangle}{\langle I^v \rangle} \tag{1}$$

where I and I^v are the received wave intensities in the atmosphere and in vacuum, respectively. < > denotes an ensemble-average. Excluding the attenuation due to turbulence scattering, the atmospheric transmittance described in LOWTRAN is

$$\tau_L = \tau_{km} \cdot \tau_{ka} \cdot \tau_{\sigma m} \cdot \tau_{\sigma a} \tag{2}$$

where K_m, σ_m, K_a, σ_a are the absorption constant and scattering cross section of the molecules and aerosols in the atmosphere, respectively. Eq.(2) implies that all scattering energy is thought as a loss. This is a good approximation for a receiver with a very narrow angle of Field of View (FOV) and for scattering by molecules and aerosols that give trivial forward scattering because of their small sizes. However, the scales of turbulence (1mm ~ 100m) are much larger than optical or infrared wavelengths. A strong forward scattering field due to turbulence is then present. Since the turbulence-induced deviation of the arrival angle is in the order of micrc-radians , the scattering energy is not completely lost for a receiver with an angle of FOV larger than micro-radians. Assuming that the scattering by molecules, aerosols and by turbulence are independent, we can then write the atmospheric transmittance τ as

$$\tau = \tau_L \langle \tau_T \rangle \tag{3}$$

where $\langle \tau_T \rangle$ is the ensemble-averaged transmittance due to turbulence.

(a) Plane wave

In turbulence, the refractive index variation is small ($\sim 10^{-6}$) and the scales of turbulence are much larger than optical or infrared wavelengths. Therefore, the backscattering due to turbulence is small. For plane waves, neglecting the trivial backscattered fields, almost all incident waves reach the receiver plane though the wavefronts are distorted and the received wave energy is redistributed through the entire receiver plane. Hence, the ensemble-averaged transmittance of a plane wave in turbulence has a value of unity, i.e.,

$$\langle \tau_T \rangle = 1 \tag{4}$$

However, the redistributed energy does degrade the coherence of the received wave and induces wave scintillation which we will discuss in section III.

The finite aperture of a receiver with radius R collects power P:

$$\langle P \rangle = I_s \tau \pi R^2 \tag{5a}$$

$$= \tau_L I_s \pi R^2 \tag{5b}$$

where I_s is the plane wave intensity in the transmitter plane. The transmittance of power can then be defined as

$$\tau_p = \frac{\langle P \rangle}{\langle P^v \rangle} = \tau_L \langle \tau_{p,T} \rangle \tag{6}$$

It is obvious the that $\langle P^v \rangle = I_s \pi R^2$. Substituting $\langle P^v \rangle$ into Eq.(6), we find that $\tau_p = \tau_L$ for a plane wave, i.e. $\langle \tau_{p,T} \rangle = 1$.

(b) Beam waves and spherical waves

The atmospheric transmittance for a beam wave is affected by the aperture size of the transmitter and receiver as well as the coherence of the source. Incorporating these parameters and using the extended Huygens-Fresnel principle, Wang and Plonus[8] derived the intensity and correlation function of the received field for a partially coherent beam wave propagating through turbulence. The intensity transmittance due to turbulence and source incoherence can then be obtained from these derivations, i.e.

$$\langle \tau_T \rangle = \frac{1 + \zeta^2 + \xi^2}{1 + \zeta^2 + f^2 + \xi^2} \tag{7}$$

where $\zeta = \alpha_s/\rho_s$, $\zeta = 2\alpha_s/\rho_o$, $f = k\alpha_s^2/L$ is the Fresnel number of the source, α_s is the source size, ρ_s is source coherence length, ρ_o is the coherence length of turbulence, L is the transmitter-receiver distance and $k = 2\pi/\lambda$. If a finite aperture receiver of radius R is used, following the definition of power transmittance $\langle \tau_{p\ T} \rangle$, Eq.(6), we have

$$\langle \tau_{p,T} \rangle = \frac{1 - \exp[-(R/\alpha_s C)^2]}{1 - \exp[-[R/\alpha_s C(\xi = 0)]^2]} \tag{8}$$

where

$$C^2 = (1 - \frac{L}{F})^2 + (1 + \xi^2 + \zeta^2)/f^2 \tag{9}$$

The detailed derivation of the intensity and power transmittance for the various limiting cases has been given in earlier reports. Here, we show some brief results.

(i) For a collimated beam ($F \to \infty$) and small receiver size ($R \to 0$) we have

$$\langle \tau_{p,T} \rangle \cong \frac{C^2(\xi = 0)}{C^2} = \langle \tau_T \rangle \tag{10}$$

The power transmittance is the same as the intensity transmittance because the received fields in the small receiver area are affected by turbulence uniformly.

(ii) Spherical wave ($\alpha_s \to 0$)

$$\langle \tau_T \rangle = \langle \tau_{p,T} \rangle = 1 \tag{11}$$

Like in the case of the plane wave, a spherical wave is affected by turbulence uniformly throughout the entire receiver area. Since no energy is lost due to turbulence scattering, turbulence does not attenuate the atmospheric transmittance (intensity or power) for spherical waves.

(iii) Incoherent sources ($\rho_s \to \frac{\lambda}{2\pi}$)

$$\langle \tau_T \rangle = \langle \tau_{P,T} \rangle = 1 \tag{12}$$

An incoherent beam wave source, acts like a spherical wave source; it radiates waves in all directions, though its field is not coherent. Hence, turbulence scatters ' wave uniformly and does not give rise

to any attenuation in the atmospheric transmittance for an incoherent source. Also, we have shown that a completely incoherent source ($\rho_s = 0$) does not radiate[9].

(iv) Coherent source ($\rho_s \rightarrow \infty$)

$$\langle \tau_T \rangle = \frac{1 + f^2}{1 + f^2 + \xi^2} \tag{13}$$

It is interesting to note that a completely coherent wave is subject to the most serious attenuation due to turbulence.

Eq.(7) expresses the atmospheric transmittance due to turbulence for a partially coherent source in the turbulent atmosphere. When the field coherence length ρ_o is larger than either the source aperture size α_s or the Fresnel zone $\sqrt{\lambda L}$, the transmittance due to turbulence is approximately unity. This is usually true for the weak turbulence case. The behavior of the power transmittance $\langle \tau_{P,T} \rangle$ is quite similar to the intensity transmittance $\langle \tau_T \rangle$ when a small aperture receiver is used. If the receiver size is large enough to collect all the scattered field due to turbulence, i.e. $R \gg \alpha_s C$, no attenuation of power occurs. Therefore, the power transmittance approaches the constant unity as $R \rightarrow \infty$. (See Eq.(8))

From the above discussion, we conclude that the atmospheric transmittance due to turbulence is definitely unity for plane waves as well as for spherical waves and approaches the value of unity for most cases of beam waves except for a coherent beam wave source in strong turbulence[10]. Hence, we have decided not to incorporate an attenuation factor due to turbulence into the calculation of atmospheric transmittance in Lowtran.

III. Transmittance fluctuation due to turbulence

The most serious effect of turbulence on wave propagation in the turbulent atmosphere is the fluctuation of the received field. We defined the scintillation index m^2 as the normalized intensity variance[2],

$$m^2 = \frac{\sigma_I^2}{\langle I\rangle^2} = \frac{\langle (I - \langle I\rangle)^2\rangle}{\langle I\rangle^2} = \frac{\langle I^2\rangle}{\langle I\rangle^2} - 1 \tag{14}$$

The power scintillation index is given by

$$m_p^2 = \frac{\sigma_p^2}{\langle P\rangle^2} = \frac{\langle (P - \langle P\rangle)^2\rangle}{\langle P\rangle^2} = \frac{\langle P^2\rangle}{\langle P\rangle^2} - 1 \tag{15}$$

where

$$P = \int_\Sigma I(\underline{p})\, d^2\underline{p} \tag{16}$$

is the wave power received by the receiver aperture Σ. We can then relate the scintillation index to the deviation of the atmospheric transmittance fluctuation. The detailed derivations of intensity and power transmittance bounds are shown in Appendix 4A and 4B in the Fourth report . From this report we obtain that

$$\tau_{\substack{u\\ \ell}} = \langle\tau\rangle\,(1 \pm m) = \tau_L\,(1 \pm m) \tag{17}$$

where τ_u and τ_ℓ are the upper and lower bounds of the transmittance, respectively. And,

$$\tau_{p_{\substack{u\\ \ell}}} = \langle\tau_p\rangle\,(1 \pm m_p) \tag{18}$$

Note that the upper and lower bounds of transmittance are not the exact bounds as some measured transmittance may be out of the bounds.

However, for many samples, we expect that most measured transmittances will fall inside these bounds. Since we concluded, in section II, that the transmittance attenuation due to turbulence scattering is not significant, the only involvement of turbulence in Eqs. (17) and (18) is in the scintillation index m^2 and m_p^2. The new subroutines VRANI and SINTL are to calculate m^2 and m_p^2 for plane waves and beam waves, respectively.

(a) Plane waves

(i) Point receiver

Consider a plane wave U propagating through the turbulent medium represented by

$$U = e^{\chi + i S} \tag{19}$$

where χ and S present the random log-amplitude and random phase due to turbulence, respectively. Assuming a Gaussian probability distribution for χ , the averaged intensity and variance of intensity can then be stated as

$$\langle I \rangle = \langle U \cdot U^* \rangle = \langle e^{2\chi} \rangle = e^{2\langle\chi\rangle + 2\sigma_\chi^2} \tag{20}$$

$$\langle I^2 \rangle = \langle U \cdot U^* U \cdot U^* \rangle = e^{4\langle\chi\rangle + 8\sigma_\chi^2} \tag{21}$$

Substituting Eqs.(20) and (21) into Eq.(14), the scintillation index for plane waves is

$$m^2 = e^{4\sigma_\chi^2} - 1 \tag{22}$$

The variance of log-amplitude, σ_χ^2, has been found by Rytov's method[6].

However, it is only valid for weak turbulence when applied in Eq.(22). Experimental data indicates that m^2 (i.e. $\sigma^2_{I_N}$) saturates toward the value of unity[6]. In recent years, theoretical work to prove that the variance of intensity saturates to a constant of unity was performed[10]. Avoiding complex mathematics and hoping to get a model which is sufficiently accurate under weak and strong turbulence conditions, we relate the variance of intensity and log-amplitude by

$$m = 1 - e^{-2\sigma^2_\chi} \tag{23}$$

For small values of σ^2_χ, $m = 2\sigma_\chi$ which agrees with Eq.(22). For large σ_χ, $m \simeq 1$, which agrees with the saturation condition. Using Ref. (7), the variance of log-amplitude as found by Rytov's method is given by

$$\sigma^2_\chi = 0.563\, k^{7/6} \int_o^L C_n^2(\eta)\, (L - \eta)^{5/6}\, d\eta \tag{24}$$

where $k = 2\pi/\lambda$ is the wavenumber.

C_n^2 is the structure constant of turbulence.

For a homogeneous medium, C_n^2 is constant along the path, and Eq.(24) can be rewritten as

$$\sigma^2_\chi = 0.31\, C_n^2\, k^{7/6}\, L^{11/6} \tag{25}$$

A model of C_n^2 for the earth's atmosphere is given by Hufnagel, et al.[11]. We will show and modify this model to fit in Lowtran later.

(ii) Finite aperture receiver

For a finite size of receiver with radius R , the average

received power for the plane wave case can then be obtained from Eq.(16),

$$\langle P\rangle = \int_\Sigma \langle I\rangle\, d^2 \underline{p} = \langle I\rangle\, \pi R^2 \tag{26}$$

and similarly the mean-square received power is

$$\langle P^2\rangle = \int_\Sigma\int_{\Sigma'} \langle II\rangle\, d^2 \underline{p}_1\, d^2 \underline{p}_2 \quad . \tag{27}$$

Assuming that χ is Gaussian, we substitute Eqs.(19), (26) and (27) into Eq.(15) and obtain m_p^2 ,

$$m_p^2 = \frac{4}{\pi R^2} \int_0^{2R} \left(e^{4B_\chi(\rho)} - 1\right) \left[\cos^{-1}\left(\frac{\rho}{2R}\right) - \left(\frac{\rho}{2R}\right)\sqrt{1 - \frac{\rho^2}{4R^2}}\right] \rho d\rho \tag{28}$$

where

$$B_\chi(\rho) \equiv \langle\chi(\underline{p})\chi(\underline{p} + \underline{\rho})\rangle \tag{29}$$

The averaging factor G(R) is defined as [2,6]

$$G(R) = m_p^2/m^2 \tag{30}$$

From Eqs. (22) and (28), we obtain the following expression for G(R),

$$G(R) = \frac{4}{\pi R^2} \int_0^{2R} b_I(\rho) \left[\cos^{-1}\left(\frac{\rho}{2R}\right) - \frac{\rho}{2R}\sqrt{1 - \frac{\rho^2}{4R^2}}\right] \rho dp \tag{31}$$

where

$$b_I(\rho) \equiv \frac{e^{4B_\chi(\rho)} - 1}{e^{4\sigma_\chi^2} - 1} \tag{32}$$

Using Rytov's Method, the Kolmogorov spectrum and a locally homogeneous medium, the correlation function of log-amplitude can be

found from Ref. (6) under the condition $L\lambda \gg l_0^2$,

$$B\chi(\rho) = 0.033\pi^2(-\Gamma N - \frac{5}{6})) k^2 \int_o^L C_n^2(\eta)\, d\eta\, J(\rho,h) \qquad (33)$$

where

$$J(\rho,\eta) = [\mathrm{Re}(\frac{1}{K_m^2} + \frac{i(L-\eta)}{k})^{5/6} {}_1F_1(-\frac{5}{6}, 1, -\frac{\rho^2}{4(\frac{1}{K_m^2} + \frac{i(L-\eta)}{k})})$$

$$-(\frac{1}{K_m^2})^{5/6}, F, (-\frac{5}{6}, 1, x) \qquad (34)$$

$$X = K_m^2\rho^2/4$$

$$K = 5.92/\ell_o \qquad (35)$$

ℓ_o is the inner scale of turbulence

${}_1F_1(a,b,x)$ is the degenerate hypergeometric function.

To calculate the power transmittance deviation in subroutine VRANI, we first obtain the G(R) factor and use the modified intensity deviation Eq.(23), that is

$$m_p = m \cdot G(R) \qquad (36)$$

(b) Beam waves and spherical waves

The extended Huygens-Fresnel principle can be used to obtain the receiver field for beam wave or spherical wave sources in the turbulent medium:

$$u(L,\underline{p}) = \frac{e^{jkL}}{j\lambda L} \int_\Sigma\int d^2\underline{s}\, \mu_s(\underline{s})\, \exp[\frac{jk}{2L}|\underline{s} - \underline{p}|^2 + \Psi(\underline{s}, \underline{\rho})] \qquad (37)$$

where $\chi(s,p) = \chi + iS$ is the random pertubation due to turbulence.

From Eq.(37), we can derive the expressions of the received intensity and intensity-correlation functions that are needed to obtain the intensity and power scintillation index. For a practical system, the source is not necessarily coherent. Thus, there could exist a random part of u(s) in Eq.(37). However, a slow-response time (narrow bandwidth) receiver can smooth out some fluctuations due to source randomness. Hence, the intensity and power scintillation index are affected , in addition to turbulence, by source incoherence and receiver response time (bandwidth).

The intensity-correlation function, which includes the effects of source incoherence and random medium due to turbulence, has been derived for a partially coherent beam wave source in turbulent medium[2], as

$$B = \langle I(\underline{p}_1) I(\underline{p}_2)\rangle$$

$$= \left(\frac{1}{\lambda L}\right)^4 \int \cdots \int d^2\underline{s}_1 d^2\underline{s}_2 d^2\underline{s}_3 d^2\underline{s}_4 \Gamma_4^s(\underline{s}_1,\underline{s}_2,\underline{s}_3,\underline{s}_4)\cdot \Gamma_4(\underline{s}_1,\underline{s}_2,\underline{s}_3,s_4;\underline{p}_1,\underline{p}_2)$$

$$\cdot \exp\{-\frac{ik}{L}[\underline{p}_1 \cdot(\underline{s}_1 - \underline{s}_2) + \underline{p}_2 \cdot (\underline{s}_3 - \underline{s}_4)] + \frac{ik}{2L}(s_1^2 + s_2^2 + s_3^2 + s_4^2)\} \tag{38}$$

where

$$\Gamma_4^s(\underline{s}_1,\underline{s}_2,\underline{s}_3,\underline{s}_4) = \langle u_s(\underline{s}_1)u_s^*(\underline{s}_2)u_s(\underline{s}_3)u_s^*(\underline{s}_4)\rangle_s \tag{39}$$

is the fourth-order source coherence function and

$$\Gamma_4^s(\underline{s}_1,\underline{s}_2,\underline{s}_3,\underline{s}_4;\underline{p}_1,\underline{p}_2) = \langle \exp[\Psi(\underline{s}_1,\underline{p}_1) + \Psi^*(\underline{s}_1,\underline{p}_1) + \Psi(\underline{s}_3,\underline{p}_2)$$

$$+ \Psi^*(\underline{s}_4,\underline{p}_2)\rangle_m \tag{40}$$

(40)

is the fourth-order spherical wave coherence function in the turbulent medium. The bracket subscripts s and m denote the ensemble averages over the statistics of source and turbulent medium, respectively.

(i) Source statistics and response time of receiver

For a receiver with response time larger than source coherent time, F_4^s in Eq.(39) reduces to a product of second-order spherical wave correlation functions[12,13] i.e.

$$F_4^s = \langle u_s(\underline{s}_1)u_s^*(\underline{s}_2)\rangle\langle u_s(\underline{s}_1)u_s^*(\underline{s}_2)\rangle \tag{41}$$

Eq.(41) makes the mathematics much simpler and correctly gives zero scintillation in vacuum. On the other hand if the response time is smaller, the fluctuations due to the source are not smoothed out. The following derivation is to model mathematically the source coherence properties and obtain a suitable expansion of Eq.(39).

For a partially (spatially) coherent source, $u_s(\underline{s})$ can be expressed by the product of the deterministic radiation distribution factor $u_{sd}(\underline{s})$ and the random coherence factor $u_{sr}(\underline{s})$. Let $u_{sd}(\underline{s})$ be a source distribution such as that of a fundamental-mode laser:

$$u_{sd}(\underline{s}) = A_s \exp[-(\frac{1}{2\alpha_s^2} + \frac{ik}{2F})s^2] \tag{42}$$

and let the random part of the source field be

$$u_{sr}(\underline{s}) = e^{i\phi(\underline{s})} \tag{43}$$

We model the random phase of the source field as[14]

$$\phi(\underline{s}) = a + \underline{b} \cdot \underline{s} \tag{44}$$

where a and $\underline{b}$ are a random shift and a random tilt vector of the random phase. Assuming the distributions of a and b are Gaussian with zero mean, we have two kinds of statistics, namely Gaussian phase statistics and pair-correlated field statistics to apply to F_4^s.

In Ref. (4), we have shown that pair-correlated statistics give the better results. The source coherence function obtained by these statistics can be stated as,

$$F_4^s(s_1,\underline{s}_2,\underline{s}_3,\underline{s}_4) = A_s^4 \exp[-\frac{1}{2\alpha_s^2}(s_1^2 + s_2^2\ s_3^2 + s_4^2) - \frac{jk}{2F}(s_1^2 - s_2^2 + s_3^2 - s_4^2)]$$

$$\cdot \Big(\exp\{-\frac{1}{4\rho_s^2}[(\underline{s}_1 - \underline{s}_2)^2 + (\underline{s}_3 - \underline{s}_4)^2]\}$$

$$+ \exp\{-\frac{1}{4\rho_s^2}[(\underline{s}_1 - \underline{s}_4)^2 + (\underline{s}_3 - \underline{s}_2)^2]\}$$

$$+ \exp\{-4\sigma_a^2 - \frac{1}{4\rho_s^2}[(\underline{s}_1 + \underline{s}_3)^2 + (\underline{s}_2 + \underline{s}_4)^2]\}$$

$$- 2\exp\{-2\sigma_a^2 - \frac{1}{4\rho_s^2}(s_1^2 + s_2^2 + s_3^2 + s_4^2)\}\Big) \qquad (45)$$

where

$$\rho_s^2 = 1/\langle b^2\rangle \qquad (46)$$

σ_a^2 is the variance of the random shift a, α_s is the beam radius and F is the radius of curvature of beam wavefront. σ_a^2 and ρ_s are measures of the degree of coherence. As $\rho_s \to \infty$, $\sigma_a^2 \to 0$, we consider the source coherent; if $\rho_s \to 0$ or/and $\sigma_a^2 \to \infty$, the source is incoherent.

(ii) Atmospheric turbulence

In weakly turbulent media, we can assume that the random pertubation Ψ is Gaussian, i.e. the log-normal field assumption is valid. The fourth-order spherical wave coherence function F_4 can then be expressed by the structure functions and correlation functions as[5]

$$F_4 = \exp\Big[-\frac{1}{2}D(\underline{s}_1-\underline{s}_2,0)-\frac{1}{2}D(\underline{s}_1-\underline{s}_4,p_d)-\frac{1}{2}D(\underline{s}_2-\underline{s}_3,\underline{p}_d)$$

$$-\frac{1}{2}D(\underline{s}_3-\underline{s}_4,0)+\frac{1}{2}D(\underline{s}_2-\underline{s}_4,p_d)+\frac{1}{2}D(\underline{s}_1-\underline{s}_3,p_d)$$

$$+2B_\chi(\underline{s}_2-\underline{s}_4,\underline{p}_d)+2B_\chi(\underline{s}_1-\underline{s}_3,p_d)$$

$$+i\,D_{\chi S}(\underline{s}_2-\underline{s}_4,p_d)-i\,D_{\chi S}(\underline{s}_1-\underline{s}_3,p_d)\Big] \tag{47}$$

where $\underline{p}_d = \underline{p}_1 - \underline{p}_2$ and D, B_χ, $D_{\chi S}$ are the wave structure function, log-amplitude correlation function and log-amplitude phase structure function, respectively. The two-wave structure functions are known.[15] Hence, for $(\lambda L)^{1/2} \gg |s_d| \gg l_0$, and by use of the quadratic approximation, we can find the wave structure functions,

$$\frac{1}{2}D(\underline{s}_d,p_d) = \frac{1}{\rho_o^2}(s_d^2 + \underline{s}_d\cdot\underline{p}_d + p_d^2) \tag{48}$$

$$D_{\chi S}(\underline{s}_d,\underline{p}_d) = \frac{-1}{\rho_{\chi S}^2}(s_d^2 + \underline{s}_d\cdot\underline{p}_d + p_d^2) \tag{49}$$

where

$$\frac{1}{\rho_o^2} = 1.575\ k^{12/5}\ L^{-2}\Big[\int_0^L d\eta(L-\eta)^{5/3}\ C_n^2(\eta)\Big]^{6/5} \tag{50}$$

$$\frac{1}{\rho_{\chi S}^2} = 0.234\ k^{13/6}\ L^{-11/6}\int_0^L d\eta\frac{Cn^2(\eta)\eta^2}{[\eta(L-\eta)]^{1/6}} \tag{51}$$

The use of the quadratic approximation for the structure functions

does not imply that we are limited to the case of tilt-only medium[15,17] because in the expansion of F_4 terms other than phase-tilt terms are present and which are retained. Fante[14] has introduced a useful log-amplitude correlation function as

$$B_\chi(\underline{s}_d,\underline{P}_d) = \sigma^2_{\chi_s}\ e^{-\frac{1}{\rho_0^2}(s_d^2 + \underline{s}_d \cdot \underline{P}_d + P_d^2)} \tag{52}$$

where

$$\sigma^2_{\chi_s} = 0.225\ k^{7/6}\int_0^L d\eta\ Cn^2(\eta)(L - \eta)^{5/6} \tag{53}$$

is the variance of log-amplitude for spherical waves[6]. To obtain a closed form result for m^2 and m_p^2 , we should further approximate Eq.(52) as

$$B_\chi\ (\underline{s}_d,\underline{P}_d) = \sigma^2_{\chi_s}\ [1 - \frac{1}{\rho_o^2}(s_d^2 + \underline{s}_d \cdot \underline{P}_d + P_d^2)] \tag{54}$$

Note that only the structure constant $C_n^2(\eta)$ contained in Eqs. (50), (51) and (53) characterizes turbulence properties. Therefore, once we know C_n^2 along the propagation path, we can obtain $\frac{1}{\rho_o^2}$, $\frac{1}{\rho_{\chi S}^2}$ and $\sigma^2_{\chi_s}$ for both homogeneous (horizontal path) and inhomogeneous (slant path) turbulent media.

The structure constant C_n^2 has been measured and modeled for the earth's atmosphere by Hufnagel, et. al.[11] We modify it to fit Lowtran as

$$C_n^2(h) = \begin{cases} 4.2 \times 10^{-14} h^{-2/3}\ \exp(-h/320) & (h > 10\ m) \\ 8.77 \times 10^{-15} & (h < 10\ m) \\ 0 & (h >s\ 100\ Km) \end{cases} \tag{55}$$

where h is the altitude in meters.

(iii) Intensity and power scintillation

A step-function receiver makes the mathematics complicated such that a closed-form of power scintillation cannot be obtained. Therefore, we integrate the given intensity and intensity-correlation function over the receiver aperture weighted by a Gaussian function, which allows us to relax the integration limits to infinity and obtain closed-form results. Using Eqs. (14), (15), (37), (38), (45) and (47), the intensity and power scintillation index for a partially coherent beam wave source in turbulence have been obtained.[2] That is,

$$m^2(p) = \frac{4\sigma_{\chi_s}^2}{\alpha_s^4}\left[\frac{1}{4\alpha_s^2} + \frac{1}{4\rho_s^2} + \frac{1}{\rho_o^2} + \left(\frac{\alpha_s A}{2}\right)^2\right]^2 \exp\left\{\left[\frac{\frac{2k^2}{L^2}}{\left[\alpha_s^2 A^2 + \frac{1}{\alpha_s^2} + \frac{4}{\rho_o^2} + \frac{1}{\rho_s^2}\right]}\right]p^2\right\}$$

$$\cdot \left\{\frac{\alpha_s^2}{2BDG} \exp\left[\frac{k^2 p^2}{BL^2}\right] + \frac{\alpha_s^2}{2BKN} \exp\left[-\frac{k^2 p^2}{BL^2}\right]\right.$$

$$\left. + \frac{e^{-4\sigma_\alpha^2}}{TUDW} \exp\left[-\frac{k^2 p^2}{UL^2}\right] - \frac{e^{-2\sigma_a^2}}{ZXYZ} \exp\left[-\frac{k^2 p^2}{YL^2}\right]\right\} - 1 \qquad (56)$$

and

$$m_p^2 = \frac{4e^{4\sigma_{\chi_s}^2}}{\alpha_s^4}\left[\frac{1}{4\alpha_s^2} + \frac{1}{4\rho_s^2} + \frac{1}{\rho_o^2} + \left(\frac{\alpha_s A}{2}\right)^2\right]^2 \left[\frac{1}{R^2} + \frac{\left(\frac{k\alpha_s^2}{L}\right)^2}{\alpha_s^2\left[1 + \left(\frac{\alpha_s}{\rho_s}\right)^2 + \left(\frac{2\alpha_s^2}{\rho_o}\right)^2 + \left(\alpha_s^2 A\right)^2\right.}\right]^2$$

$$\cdot \left[\frac{\alpha_s^2}{2BDG\left(H_1 + \frac{2}{R^2}\right)\left(F_1 + \frac{1}{2R^2}\right)} + \frac{\alpha_s^2}{2BKN\left(H^2 + \frac{2}{R^2}\right)\left(F^2 + \frac{1}{2R^2}\right)} \right.$$

$$\left. + \frac{e^{-4\sigma_a^2}}{TUDG\left(H_3 + \frac{2}{R^2}\right)\left(F_3 + \frac{1}{2R^2}\right)} - \frac{e^{-2\sigma_a^2}}{2XYZQ\left(H_4 + \frac{1}{R}\right)\left(F_4 + \frac{1}{2R^2}\right)} \right] -1 \tag{57}$$

where

$$H_1 = H_2 = \frac{k^2}{BL^2}$$

$$H_3 = \frac{k^2}{UL^2}$$

$$H_4 = \frac{k^2}{YL^2}$$

$$F_1 = \frac{4\sigma_{\chi_s}^2}{\rho_o^2} - \frac{1}{D}\left(\frac{2\sigma_{\chi_s}^2}{\rho_o^2}\right)^2 + \frac{\frac{2\sigma_{\chi_s}^2}{D\rho_o^2}\left(A - \frac{4}{\rho_{\chi S}}\right) + \frac{k}{L} + \frac{1}{\rho_{\chi S}}]^2}{4G}$$

$$F_2 = \frac{4\sigma_{\chi}^2}{\rho_o^2} \quad \frac{1}{K}\left(\frac{2\sigma_{\chi_s}^2}{\rho_o^2}\right)^2 + \frac{\left[\frac{2\sigma_{\chi_s}^2}{K\rho_o^2}\left(A - \frac{4}{\rho_{\chi S}^2}\right) + \frac{k}{L} + \frac{1}{\rho_{\chi S}^2}\right]^2}{4N}$$

$$F_3 = \frac{4\sigma_{\chi_s}^2}{\rho_o^2} \quad \frac{1}{D}\left(\frac{2\sigma_{\chi_s}}{\rho_o^2}\right)^2 + \frac{\left[\frac{2\sigma_{\chi_s}^2}{D\rho_o^2}\left(A - \frac{4}{\rho_{\chi S}^2}\right) + \frac{k}{L} + \frac{1}{\rho_{\chi S}^2}\right]^2}{4W}$$

$$F_4 = \frac{4\sigma^2_{\chi_S}}{\rho_o^2} - \frac{1}{Q}\left(\frac{2\sigma^2_{\chi_S}}{\rho_o^2}\right)^2 + \frac{\left[\frac{2\sigma^2_{\chi_S}}{Q\rho_o^2}\left(A - \frac{4}{\rho^2_{\chi S}} + \frac{k}{L} + \frac{1}{\rho^2_{\chi S}}\right)\right]^2}{4Z}$$

$$B = \frac{1}{2\alpha_s^2} + \frac{1}{2\rho_s^2} + \frac{\alpha_s^2 A^2}{2} + \frac{4}{\rho_o^2}$$

$$D = \frac{1}{2\alpha_s^2} + \frac{4\sigma^2_{\chi_S}}{\rho_o^2}$$

$$G = D + \frac{1}{2\rho_s^2} + \frac{\left(A - \frac{4}{\rho^2_{\chi S}}\right)^2}{4D}$$

$$K = D + \frac{1}{2\rho_s^2}$$

$$N = D + \frac{\left(A - \frac{4}{\rho^2_{\chi S}}\right)^2}{4K}$$

$$T = \frac{2}{\alpha_s^2} + \frac{2}{\rho_s^2}$$

$$U = \frac{T}{4} + \frac{A^2}{T} + \frac{4}{\rho_o^2} = \frac{A^2}{T} + \frac{1}{2\rho_S^2} + \frac{1}{2\alpha_s^2} + \frac{4}{\rho_o^2}$$

$$W = G - \frac{1}{1\rho_s^2}$$

$$X = \frac{1}{2\alpha_s^2} + \frac{1}{4\rho_s^2}$$

$$Y = X + \frac{A}{4X} + \frac{4}{\rho_o^2}$$

$$O = D + \frac{1}{4\rho_s^2}$$

$$Z = Q + \frac{\left(A - \frac{1}{\rho_{\chi s}^2}\right)^2}{4Q}$$

(58)

Instead of [illegible]ng $B_\chi = \sigma_\chi^2 - \frac{1}{2} D_\chi$, we have used Eq. (52) for the log-amplitude correlation function. Therefore, we substitute $(\frac{1}{\rho_o^2} - \frac{1}{\rho_\chi^2})$ by $(\frac{2\sigma_{\chi_s}^2}{\rho_o^2})$ for all terms in Eq. (59) which can be obtained from Ref. (2). This substitution gives the better results, even though the application range for the approximation is still limited[16].

By letting $\alpha_s \to 0$, we can obtain the spherical wave results. The intensity and power transmittance deviations for beam waves and spherical waves can then be calculated by the SINTL computer code using Eqs. (56) and (57).

IV. Subroutine VRANI

The subroutine VRANI is designed to calculate, by using Eqs. (23) - (36), the plane wave intensity and power variance.

For the program, we changed the integration in all formulas to the summation form. From Eq.(55), we find that C_n^2 varies rapidly when height h is small. By trading off calculation time and precision of C_n^2, we choose the subintervals in the summation as,

$$
\begin{aligned}
\Delta h_{ij} &= 20 \text{ m} & h_{ij} &< 25 \text{ km} \\
\Delta h_{ij} &= 100 \text{ m} & 25 \text{ km} < h_{ij} &< 50 \text{ km} \qquad (59) \\
\Delta h_{ij} &= 400 \text{ m} & 50 \text{ km} < h_{ij} &< 100 \text{ km}
\end{aligned}
$$

Eq.(24) can then be rewritten as

$$\sigma_\chi^2 = 0.56\ k^{7/6} \sum_i \sum_j C_n^2(h_{ij})(L - L_{ij})^{5/6} \frac{\Delta L_i}{h_i - h_{i-1}} \Delta h_{ij} \qquad (60)$$

where h_{ij} is the height which corresponds to the calculated points on the path, "i" is the layer index, "j" is the sub index of each layer, L is the total path length, L_i is the path range from the transmitter to the point calculated and ΔL_i is the path range for each layer passed.

Since the structure constant C_n^2 depends on h, the calculation for horizontal and slant paths are different.

(a) Horizontal path

The intensity variance m^2 can be obtained by Eqs. (23) and (25) after the constant C_n^2 is specified. $B_\chi(\rho)$ can be found with the condition that $\ell_o^2 \ll \lambda L$ by using Rytov's Method and Kolmogorov spectrum[6,17],

$$B_\chi(\rho) = b_\chi(\rho)\sigma_\chi^2 \qquad (61)$$

and

$$b_\chi(\rho) = \begin{cases} 1 - 12.3\dfrac{\rho^2}{(\lambda)^{5/6}\,\ell_o^{1/3}} & \rho << \ell_o \\[2ex] 1 - 2.36\left(\dfrac{k\rho^2}{L}\right)^{5/6} + 1.71\dfrac{k\rho^2}{L} - 0.024\left(\dfrac{k\rho^2}{L}\right)^2 & \ell_o << \ell << \sqrt{\lambda L} \\[2ex] -\ 0.0242\left(\dfrac{k\rho^2}{4L}\right)^{-7/6} & \sqrt{\lambda L} << \rho \end{cases} \qquad (62)$$

where ℓ_o is the inner scale of turbulence and is assumed to be 3 mm in our subroutine. The power variance can then be obtained by Eqs. (31) and (36).

(b) Slant path

Eq. (60) can be used to calculate the intensity variance for the slant path cases. To obtain results for power variance, Eqs. (33) and (34) have to be approximated so that the integration can be changed to a summation from. The calculation for power variance can then be performed. The approximations are

$$ {}_1F_1\left(-\frac{5}{6}, 1, x\right) = \begin{cases} 1 - 0.8333x - .0347x^2 - 0.0045x^3 & |x| < 6.5 \\[1ex] 1.0627\,(-x)^{5/6} & |x| \geq 6.5 \text{ and } (\mathrm{Re}\ x < 0) \end{cases} \qquad (63)$$

and

$$\begin{cases} 0 & (y > 6.5,\ x > 6.5) \\[1ex] \left(\dfrac{L-\eta}{k}\right)^{5/6}(0.259 + 0.805y + 0.009y^2 - 0.0043y^3) & \end{cases}$$

$$- 1.065y^{5/6} \qquad (y < 6.5,\ x > 6.5)$$

$$J(\eta,\rho) = \tag{64}$$

$$\left(\frac{L-\eta}{k}\right)^{5/6}(0.259 + 0.805y + 0.009y^2 - 0.0043y^3)$$

$$- \left(\frac{1}{K_m}\right)^{5/6}(1 + 0.8333x - 0.0347x^2 + 0.0045x^3)$$

$$(y < 6.5,\ x < 6.5)$$

where

$$x = - K_m^2\ \rho^2/4 \tag{65}$$

$$y = \frac{\rho^2 k}{4(L - \eta)} \tag{66}$$

The approximations have been checked and the total error is under 10%. Furthermore, we also assume that $\frac{L-\eta}{k} >> \frac{1}{K_m^2}$ which means that we neglect a very small part of turbulence near the receiver.

The subroutine VRANI is called by another subroutine TRANS in Lowtran, which calculates the atmospheric transmittance due to absorption and scattering of molecules and aerosal. The program is listed in Appendix B and the definitions of symbols and variables are shown in Appendix A.

For comparision, we used the 1962 U.S. standard atmospheric model the rural aerosal model with visual range of 23km and a 5km propagation distance to plot all the figures. For horizontal paths an altitude of 400m is used for all figures. For an upward path, the altitudes of transmitters and receivers are set to 800m and 400m, repectively. For a downward path, the altitudes of transmitter and receiver are reversed.

Figs. 1 - 3 show the plane wave intensity transmittance for horizontal, downward and upward paths, respectively. Figs. 4 - 6 give the power transmittance for the same condition except that a 10cm receiver is used. The latter figures display a smaller transmittance deviation (scintillation). This is due to the receiver aperture averaging effect.

V. Subroutine SINTL

The subroutine SINTL calculates the intensity and power variance for partially coherent beam wave and spherical wave sources.

(a) Horizontal path

C_n^2 is constant along the path for the horizontal case. Eqs. (50), (51) and (53) can then be rewritten as

$$\frac{1}{\rho_o^2} = (0.546\ C_n^2\ k^2\ L)^{6/5} \tag{67}$$

$$\frac{1}{\rho_{\chi S}^2} = 0.114 C_n^2\ k^{13/6}\ L^{5/6} \tag{68}$$

$$\sigma_{\chi_s}^2 = 0.124\ C_n^2\ k^{7/6}\ L^{11/6} \tag{69}$$

After the C_n^2 constant is calculated from Eq. (55), $\frac{1}{\rho_o^2}$, $\frac{1}{\rho_{\chi S}^2}$ and $\sigma_{\chi_s}^2$ can be obtained immediately from the above equations. Eq. (56) will then give the result of the intensity scintillation for a partially coherent beam wave source.

(b) Slant path

Changing the integrations in Eqs. (50), (51) and (53) into summation form, like that of Eq. (60), we can obtain the results for $\frac{1}{\rho_o^2}$, $\frac{1}{\rho_{\chi S}^2}$ and $\sigma_{\chi_s}^2$. The power scintillation (variance) can then be calculated by the closed-form formula of Eq. (57).

SINTL is also called by the subroutine TRANS when the transmitter size is finite. The program list is shown in Appendix C.

Figs. 7 - 9 show the intensity transmittance for partially

coherent beam wave sources in horizontal, downward and upward paths, respectively. For the finite receiver with radius of 10cm, Figs. 10 - 12 give the power transmittance. Again, the receiver aperture averaging effect can be found by comparing the intensity and power transmittance deviations. The results of spherical wave cases are shown in Figures 13 - 15 and Figures 16 - 18 for point receivers and finite aperture recievers, respectively.

APPENDIX A

Symbols and Defintions for Subroutines VRANI and SINTL

ANGLE Initial zenith angle in degree

BI Covariance of intensity

BL Log-amplitude covariance normalized by variance

BX Covariance of log-amplitude

CN2 C_n^2 - structure constant of turbulence

DD the ratio of the distance from point calculated to receiver over total path length.

DH Height interval of slant path integration

DO Distance from point calculated to transmitter

DS Distance from point calculated to receiver

DSW Path length in a layer

DT Same as DS, especially used in the downward long path calculation

DZW Height for a layer

FR Fresnel zone in meter (m)

GAA σ_a^2, variance of random shift for a partially coherent source. It is assumed to be zero for a temporal coherent source.

GD Aperture averaging factor

HMIN The minimum height of a downward path

HW Height corresponding to the point calculated

H1 Height of receiver (and transmitter for horizontal path)

H2 Height of transmitter

IV Wavenumber in cm^{-1}

JMIN The layer index of the minimum height for a downward path

PVR Power variance

RANGE Path length in kilometer (km)

RLO $1/\rho_o^2$, ρ_o is the field coherence length of spherical waves

RLS Coherence length of source field

RLXS $1/\rho_{\chi S}^2$, $\rho_{\chi S}$ is the structure constant of the log-amplitude and phase structure function

RR Radius of receiver aperture in meter (m)

SIGM Variance of log-amplitude for spherical waves

SMI Intensity scintillation index

SMP Power scintillation index

TT Radius of transmitter aperture in meter (m)

VR Variance of log-amplitude for plane waves

VRI Intensity deviation

WH2 Height of receiver in meter (m)

WL Wavelength in meter (m)

WK $2\pi/\lambda$, wavenumber in m^{-1}

WRANGE Path length in meter (m)

WV Intensity variance without approximation

XW1 The lowest height of a given path in a given layer

XW2 The highest height of a given path in a given layer

APPENDIX B

```
      SUBROUTINE VRANI(IV)
C
C     THIS SUBROUTINE IS TO CALCULATE THE VARIANCE OF INTENSITY
C     DUE TO TURBULENCE  AND THE CALCULATED STANDARD DEVIATION CAN BE
C     USED TO DEFINE HIGH BOUND AND LOW BOUND OF TRANSMITTANCE
C
      COMMON /CARD1/ MODEL,IHAZE,ITYPE,LEN,JP,IM,M1,M2,M3,ML,IEMISS,RO
     1 ,TBOUND,ISEASN,IVULCN,VIS
      COMMON /CARD2/ H1,H2,ANGLE,RANGE,BETA,HMIN,RE,TT,RR
      COMMON /CARD3/ V1,V2,DV,AVM,CO,CW,W(15),E(15),CA,PI
      COMMON /CNTRL/ LENST,KMAX,M,IJ,J1,J2,JMIN,JEXTRA,IL,IKMAX,NLL,NP1
     1,IFIND,NL,IKLO
      COMMON /WANG/ K2,DSW(34),DZW(34),XW1(34),XW2(34)
      COMMON /VRAN/ VRI
      DIMENSION WS(34)
      HW=H1*1000.0
      WRANGE=RANGE*1000.0
      WH2=H2*1000.0
      VR=0.0
      CN2=0.0
      PVR=0.0
      WL=0.01/IV

      FR=(WL*WRANGE)**0.5
      WK=IV*100.*2.*PI
      VK=WK**(7./6.)
      WO=9.E-6/5.910**2.
      IF(ITYPE.NE.1) GO TO 20
C
C      VARIANCE CALCULATION FOR HORIZONTAL PATH
C
      CN2=4.2E-14*HW**(-2./3.)*EXP(-HW/320.0)
      IF(H1.GT.100.0) CN2=0.0
      IF(HW.LE.10.0) CN2=8.77E-15
      VR=0.31*CN2*WRANGE**(11./6.)
      VR=VR*VK
      VRI=1.-EXP(-2.*VR**0.5)
      IF(RR.LT.0.001) GO TO 91
      DO 18 I=1,100
      Y=0.01*I
      DY=RR*2.*Y
      IF(DY.GE.0.003) GO TO 11
      BL=1.-12.3*DY**2.0/(FR**(5./3.)*0.003**(1./3.))
      GO TO 17
   11 XI=WK*DY**2.0/WRANGE
```

```
      IF(DY.GE.FR) GO TO 12
      BL=1.-2.36*XI**(5./6.)+1.71*XI-0.024*XI**2.0
      GO TO 17
   12 BL=-0.0242*(XI/4.)**(-7./6.)
   17 CONTINUE
      BX=BL*VR
      BI=EXP(4.0*BX)-1.
      PVR=PVR+BI*(ACOS(Y)-Y*(1.-Y**2.)**0.5)*Y*0.01
   18 CONTINUE
      PVR=PVR*16./PI
      WV=EXP(4.0*VR)-1.
      GD=PVR/WV
      VRI=VRI*GD**0.5
      GO TO 91
   20 IF(ANGLE.GT.90.0) GO TO 37
C
C      VARIANCE CALCULATION FOR UPWARD PATH
C
      DO 35 K=1,50
      DS=0.1
      BX=0.0
      Y=0.02*K

      DY=RR*2.*Y
      RF=DY**2./4.
      VR=0.0
      Q=RF/WO
      DO 34 I=J1,J2
      WS(I)=DSW(I)/DZW(I)
      IF(XW1(I).LE.25.0) GO TO 21
      IF(XW1(I).LE.50.0) GO TO 22
      DH=400.0
      GO TO 23
   21 DH=20.0
      GO TO 23
   22 DH=100.0
   23 WIK=(XW2(I)-XW1(I))*1000.0/DH
      IK=WIK
      HW=XW1(I)*1000.0
      DO 33 J=1,IK
      HW=HW+DH
      IF(HW.GE.99600.0.AND.ITYPE.EQ.3) XW2(I)=100000.0
      IF(HW.GE.99600.0) GO TO 34
      CN2=4.2E-14*HW**(-2./3.)*EXP(-HW/320.0)
      IF(HW.GT.100000.) CN2=0.0
```

```
      IF(HW.LE.10.) CN2=8.77E-15
      VR=VR+0.56*CN2*DS**(5./6.)*DH*WS(I)
      DD=DS/WK
      R=RF/DD
      IF(DD.LT.WO) GO TO 27
      IF(R.GE.6.5.AND.Q.GE.6.5) GO TO 27
      IF(R.LT.6.5.AND.Q.LT.6.5) GO TO 28
      G=DD**(5./6.)*(0.259+0.805*R+0.009*R**2.-0.0043*R**3.)-1.063*RF**(
     *5./6.)
      IF(G.LE.0.0) G=0.
      GO TO 31
   27 G=0.0
      GO TO 31
   28 G=DD**(5./6.)*(0.259+0.805*R+0.009*R**2.-0.0043*R**3.)-WO**(5./6.)
     **(1.+0.8333*Q-0.0347*Q**2.+0.0045*Q**3.)
      IF(G.LE.0.0) G=0.0
   31 BX=BX+G*CN2*DH*WS(I)
      DS=DS+DH*WS(I)
   33 CONTINUE
      DQ=WRANGE-DS
      IF(DQ.LE.0.) DS=DS-DH*WS(I)
      VR=VR+0.56*CN2*DS**(5./6.)*(XW2(I)*1000.-HW)*WS(I)

      BX=BX+CN2*G*(XW2(I)*1000.-HW)*WS(I)
      DS=DS+(XW2(I)*1000.0-HW)*WS(I)
   34 CONTINUE
      IF(RR.LT.0.001) GO TO 36
      BX=BX*2.117*WK**2.
      BI=EXP(4.*BX)-1.
      PVR=PVR+BI*(ACOS(Y)-Y*(1.-Y**2.)**0.5)*Y*0.01
   35 CONTINUE
      PVR=PVR*16./PI
   36 VR=VR*VK
      VRI=1.-EXP(-2.*VR**0.5)
      IF(RR.LT.0.001) GO TO 91
      WV=EXP(4.*VR)-1.
      GD=PVR/WV
      VRI=VRI*GD**0.5
      GO TO 91
   37 CONTINUE
C
C       VARIANCE CALCULATION FOR DOWNWARD PATH
C
      DO 62 MW=1,50
      DS=0.1
```

```
      DT=0.1
      BX=0.0
      Y=0.02*MW
      DY=RR*2.*Y
      RF=DY**2./4.
      VR=0.0
      Q=RF/WO
      L1=J1
      DO 60 L=1,NL
      WS(L1)=DSW(L1)/DZW(L1)
      IF(XW1(L1).LE.25.0) GO TO 38
      IF(XW1(L1).LE.50.0) GO TO 39
      DH=400.0
      GO TO 40
   38 DH=20.00
      GO TO 40
   39 DH=100.00
   40 WIK=(XW1(L1)-XW2(L1))*1000.0/DH
      IK=WIK
      HW=XW1(L1)*1000.0
      DO 57 J=1,IK
      HW=HW-DH

      CN2=4.2E-14*HW**(-2./3.)*EXP(-HW/320.0)
      IF(HW.GT.100000.) CN2=0.0
      IF(HW.LE.10.) CN2=8.77E-15
      VR=VR+0.56*CN2*DS**(5./6.)*DH*WS(L1)
      DD=DS/WK
      R=RF/DD
      IF(DD.LT.WO) GO TO 51
      IF(R.GE.6.5.AND.Q.GE.6.5) GO TO 51
      IF(R.LT.6.5.AND.Q.LT.6.5) GO TO 52
      G1=DD**(5./6.)*(0.259+0.805*R+0.009*R**2.-0.0043*R**3.)-1.063*RF**
     *(5./6.)
      IF(G1.LE.0.) G1=0.
      GO TO 53
   51 G1=0.0
      GO TO 53
   52 G1=DD**(5./6.)*(0.259+0.805*R+0.009*R**2.-0.0043*R**3.)-WO**(5./6.
     *)*(1.+0.8333*Q-0.0347*Q**2.+0.0045*Q**3.)
      IF(G1.LE.0.0) G1=0.0
   53 BX=BX+G1*CN2*DH*WS(L1)
      DS=DS+DH*WS(L1)
      IF(K2.EQ.0) GO TO 57
      IF(K2.EQ.1.AND.WH2.LE.HW) GO TO 57
```

```
      VR=VR+0.56*CN2*(WRANGE-DT)**(5./6.)*DH*WS(L1)
      DD=(WRANGE-DT)/WRANGE
      R=RF/DD
      IF(DD.LT.WO) GO TO 54
      IF(R.GE.6.5.AND.Q.GE.6.5) GO TO 54
      IF(R.LT.6.5.AND.Q.LT.6.5) GO TO 55
      G2=DD**(5./6.)*(0.259+0.805*R+0.009*R**2.-0.0043*R**3.)-1.063*RF**
     *(5./6.)
      IF(G2.LE.0.) G2=0.
      GO TO 56
   54 G2=0.0
      GO TO 56
   55 G2=DD**(5./6.)*(0.259+0.805*R+0.009*R**2.-0.0043*R**3.)-WO**(5./6.
     *)*(1.+0.8333*Q-0.0347*Q**2.+0.0045*Q**3.)
      IF(G2.LE.0.0) G2=0.0
   56 BX=BX+G2*CN2*DH*WS(L1)
      DT=DT+DH*WS(L1)
   57 CONTINUE
      DQ=WRANGE-DS
      IF(DQ.LE.0.) DS=DS-DH*WS(L1)
      VR=VR+0.56*CN2*DS**(5./6.)*(HW-XW2(L1)*1000.)*WS(L1)
      BX=BX+G1*CN2*(HW-XW2(L1)*1000.)*WS(L1)

      DS=DS+(HW-XW2(L1)*1000.0)
      IF(K2.EQ.0) GO TO 58
      IF(K2.EQ.1.AND.WH2.LE.HW) GO TO 58
      VR=VR+0.56*CN2*(WRANGE-DT)**(5./6.)*(HW-XW2(L1)*1000.)*WS(L1)
      BX=BX+G2*CN2*(HW-XW2(L1)*1000.)*WS(L1)
      DT=DT+(HW-XW2(L1)*1000.0)*WS(L1)
   58 CONTINUE
      L1=L1-1
      IF(K2.EQ.0.AND.L1.LE.J2) GO TO 61
      IF(L1.LE.JMIN.AND.K2.EQ.1) GO TO 61
   60 CONTINUE
   61 CONTINUE
      IF(RR.LT.0.001) GO TO 90
      BX=BX*2.117*WK**2.
      BI=EXP(4.*BX)-1.
      PVR=PVR+BI*(ACOS(Y)-Y*(1.-Y**2.)**0.5)*Y*0.01
   62 CONTINUE
      PVR=PVR*16./PI
   90 VR=VR*VK
      VRI=1.-EXP(-2.*VR**0.5)
      IF(RR.LT.0.001) GO TO 91
      WV=EXP(4.*VR)-1.
```

```
      GD=PVR/WV
      VRI=VRI*GD**0.5
   91 CONTINUE
      RETURN
      END
```

APPENDIX C

```
      SUBROUTINE SINTL(IV)
C
C     THIS SUBROUTINE IS TO CALCULATE THE VARIANCE OF INTENSITY OR
C     POWER DUE TO TURBULENCE FOR  SPHERICAL WAVE SOURCE OR BEAM WAVE
C     WITH PARTIALLY COHERENT SOURCE
C     THE CALCULATED STANDARD DEVIATION CAN BE USED TO DEFINE
C     HIGH BOUND AND LOW BOUND OF TRANSMITTANCE
C
      COMMON /CARD1/ MODEL,IHAZE,ITYPE,LEN,JP,IM,M1,M2,M3,ML,IEMISS,RO
     1 ,TBOUND,ISEASN,IVULCN,VIS
      COMMON /CARD2/ H1,H2,ANGLE,RANGE,BETA,HMIN,RE,TT,RR,RLS
      COMMON /CARD3/ V1,V2,DV,AVM,CO,CW,W(15),E(15),CA,PI
      COMMON /CNTRL/ LENST,KMAX,M,IJ,J1,J2,JMIN,JEXTRA,IL,IKMAX,NLL,NP1
     1,IFIND,NL,IKLO
      COMMON /WANG/ K2,DSW(34),DZW(34),XW1(34),XW2(34)
      COMMON /VRAN/ VRI
      DIMENSION WS(34)
      HW=H1*1000.0
      WRANGE=RANGE*1000.0
      WH2=H2*1000.0
      GAA=0.
      TLO=0.

      TLX=0.
      TLG=0.
      CN2=0.0
      WL=0.01/IV
      FR=(WL*WRANGE)**0.5
      WK=IV*100.*2.*PI
      VK=WK**(7./6.)
      DC=TT/RLS
      WK2=WK**2.
      WR2=WRANGE**2.
      AM=WK/WRANGE
      SA=AM**2.
      IF(RLS.LT.0.0001) RLS=0.0001
      RW=1./RLS**2.
      STT=TT**2.
      IF(ITYPE.NE.1) GO TO 20
C
C      VARIANCE CALCULATION FOR HORIZONTAL PATH
C
      CN2=4.2E-14*EXP(-HW/320.)/HW**0.667
      IF(H1.GT.100.0) CN2=0.0
      IF(HW.LE.10.0) CN2=8.77E-15
```

```
      SIGM=0.124*CN2*VK*WRANGE**1.833
      RLO=(0.546*CN2*WK2*WRANGE)**1.2
      RLX=0.425*CN2*WK**2.167*WRANGE**0.833
      RLXS=0.114*RLX/0.425
      GO TO 80
   20 IF(ANGLE.GT.90.0) GO TO 37
C
C       VARIANCE CALCULATIONFOR UPWARD PATH
C
      DS=0.1
      DO 34 I=J1,J2
      WS(I)=DSW(I)/DZW(I)
      IF(XW1(I).LE.25.0) GO TO 21
      IF(XW1(I).LE.50.0) GO TO 22
      DH=400.0
      GO TO 23
   21 DH=20.0
      GO TO 23
   22 DH=100.0
   23 WIK=(XW2(I)-XW1(I))*1000.0/DH
      IK=WIK
      HW=XW1(I)*1000.0

      DO 33 J=1,IK
      HW=HW+DH
      IF(HW.GE.99600.0.AND.ITYPE.EQ.3) XW2(I)=100000.0
      IF(HW.GE.99600.0) GO TO 34
      CN2=4.2E-14*EXP(-HW/320.)/HW**0.667
      IF(HW.LE.10.0) CN2=8.77E-15
      DQ=WRANGE-DS
      TLG=TLG+CN2*DS**0.833*DH*WS(I)
      TLO=TLO+CN2*DS**1.667*DH*WS(I)
      TLX=TLX+CN2*DQ**1.833*DH*WS(I)/DS**0.167
      DS=DS+DH*WS(I)
   33 CONTINUE
      DQ=WRANGE-DS
      IF(DQ.LE.0.) DS=DS-DH*WS(I)
      IF(DQ.LE.0.) DQ=DQ+DH*WS(I)
      XY=(XW2(I)*1000.-HW)*WS(I)
      IF(XY.LE.0.) GO TO 34
      TLG=TLG+CN2*DS**0.833*XY
      TLO=TLO+CN2*DS**1.667*XY
      TLX=TLX+CN2*DQ**1.833*XY/DS**0.167
      DS=DS+XY
   34 CONTINUE
```

```
      GO TO 75
   37 CONTINUE
C
C      VARIANCE CALCULATION FOR DOWNWARD PATH
C
      DS=0.1
      DT=0.1
      L1=J1
      DO 60 L=1,NL
      WS(L1)=DSW(L1)/DZW(L1)
      IF(XW1(L1).LE.25.0) GO TO 38
      IF(XW1(L1).LE.50.0) GO TO 39
      DH=400.0
      GO TO 40
   38 DH=20.00
      GO TO 40
   39 DH=100.00
   40 WIK=(XW1(L1)-XW2(L1))*1000.0/DH
      IK=WIK
      HW=XW1(L1)*1000.0
      DO 57 J=1,IK
      HW=HW-DH

      CN2=4.2E-14*EXP(-HW/320.)/HW**0.667
      IF(HW.LE.10.0) CN2=8.77E-15
      DQ=WRANGE-DS
      TLG=TLG+CN2*DS**0.833*DH*WS(L1)
      TLO=TLO+CN2*DS**1.667*DH*WS(L1)
      TLX=TLX+CN2*DQ**1.833*DH*WS(L1)/DS**0.167
      DS=DS+DH*WS(L1)
      IF(K2.EQ.0) GO TO 57
      IF(K2.EQ.1.AND.WH2.LE.HW) GO TO 57
      TLG=TLG+CN2*(WRANGE-DT)**0.833*DH*WS(L1)
      TLO=TLO+CN2*(WRANGE-DT)**1.667*DH*WS(L1)
      TLX=TLX+CN2*DT**1.833*DH*WS(L1)/(WRANGE-DT)**0.167
      DT=DT+DH*WS(L1)
   57 CONTINUE
      DQ=WRANGE-DS
      IF(DQ.LT.0.) DQ=DQ+DH*WS(L1)
      IF(DQ.LT.0.) DS=DS-DH*WS(L1)
      XY=(HW-XW2(L1)*1000.)*WS(L1)
      IF(XY.LE.0.) GO TO 61
      TLG=TLG+CN2*DS**0.833*XY
      TLO=TLO+CN2*DS**1.667*XY
      TLX=TLX+CN2*DQ**1.833*XY/DS**0.167
```

```
      DS=DS+XY
      IF(K2.EQ.0) GO TO 58
      IF(K2.EQ.1.AND.WH2.LE.HW) GO TO 58
      TLG=TLG+CN2*(WRANGE-DT)**0.833*XY
      TLO=TLO+CN2*(WRANGE-DT)**1.667*XY
      TLX=TLX+CN2*DT**1.833*XY/(WRANGE-DT)**0.167
      DT=DT+XY
   58 CONTINUE
      L1=L1-1
      IF(K2.EQ.0.AND.L1.LE.J2) GO TO 61
      IF(L1.LE.JMIN.AND.K2.EQ.1) GO TO 61
   60 CONTINUE
   61 CONTINUE
   75 CONTINUE
      SIGM=0.225*VK*TLG
      RLO=1.575*WK**2.4*TLO**1.2/WRANGE**2.
      RLXS=0.235*WK*VK*TLX/WRANGE**1.833
   80 CONTINUE
      F4=EXP(4.*SIGM)
C
C       CALCULATION FOR SPHERICAL WAVES
C
      IF(TT.GE.0.001) GO TO 81
      F5=1.+RR**2.*SIGM*RLO*8.
      SMP=F4/F5*(2.+EXP(-4.*GAA)-2.*EXP(-2.*GAA))-1.
      GO TO 89
   81 CONTINUE
C
C       CALCULATION FOR BEAM WAVES
C
      RDI=1./STT
      F1=4.*RDI**2.
      TM=2.*RDI+2.*RW
      XM=0.5*RDI+0.25*RW
      HX=RLO*SIGM*2.
      AML=AM-RLXS*4.
      AMLS=AML**2.
      BM=0.25*TM+STT*SA/2.+4.*RLO
      DM=0.5*RDI+HX*2.
      EK=DM+0.5*RW
      GM=EK+AMLS/(4.*DM)
      EN=DM+AMLS/(4.*EK)
      QM=DM+0.25*RW
      UM=SA/TM+0.25*TM+4.*RLO
```

```
      WM=GM-0.5*RW
      YM=XM+SA/(4.*XM)+4.*RLO
      ZM=QM+AMLS/(4.*QM)
      HA=SA/BM
      HB=SA/UM
      HC=SA/YM
      F2=(TM/8.0+RLO+STT*SA/4.)**2.
      FA=0.5*STT/(BM*DM*GM)
      FB=0.5*STT/(BM*EK*EN)
      FC=EXP(-4.*GAA)/(TM*UM*DM*WM)
      FD=EXP(-2.*GAA)/(2.*XM*YM*QM*ZM)
      F3=FA+FB+FC-FD
      SMI=F1*F2*F3*F4-1.
      IF(SMI.LE.0.) SMI=0.
      VRI=SMI**0.5
      IF(RR.LT.0.001) GO TO 90
      SF1=HX*2.-HX**2./DM+(AML*HX/DM+AM+RLXS*2.)**2./(GM*4.)
      SF2=HX*2.-HX**2./EK+(AML*HX/EK+AM+RLXS*2.)**2./(EN*4.)
      SF3=HX*2.-HX**2./DM+(AML*HX/DM+AM+RLXS*2.)**2./(WM*4.)
      SF4=HX*2.-HX**2./QM+(AML*HX/QM+AM+RLXS*2.)**2./(ZM*4.)
      Q1=F1*F2*F4
      Q2=STT*SA/(1.+DC**2.+STT**2.*SA+STT*4.*RLO)

      RR2=1./RR**2.
      Q3=FA/((SF1+RR2*0.5)*(HA+RR2*2.))
      Q4=FB/((SF2+RR2*0.5)*(HA+RR2*2.))
      Q5=FC/((SF3+RR2*0.5)*(HB+RR2*2.))
      Q6=FD/((SF4+RR2*0.5)*(HC+RR2*2.))
      SMP=Q1*(Q2+RR2)**2.*(Q3+Q4+Q5-Q6)-1.
   89 IF(SMP.LE.0.) SMP=0.
      VRI=SMP**0.5
   90 CONTINUE
      RETURN
      END
```

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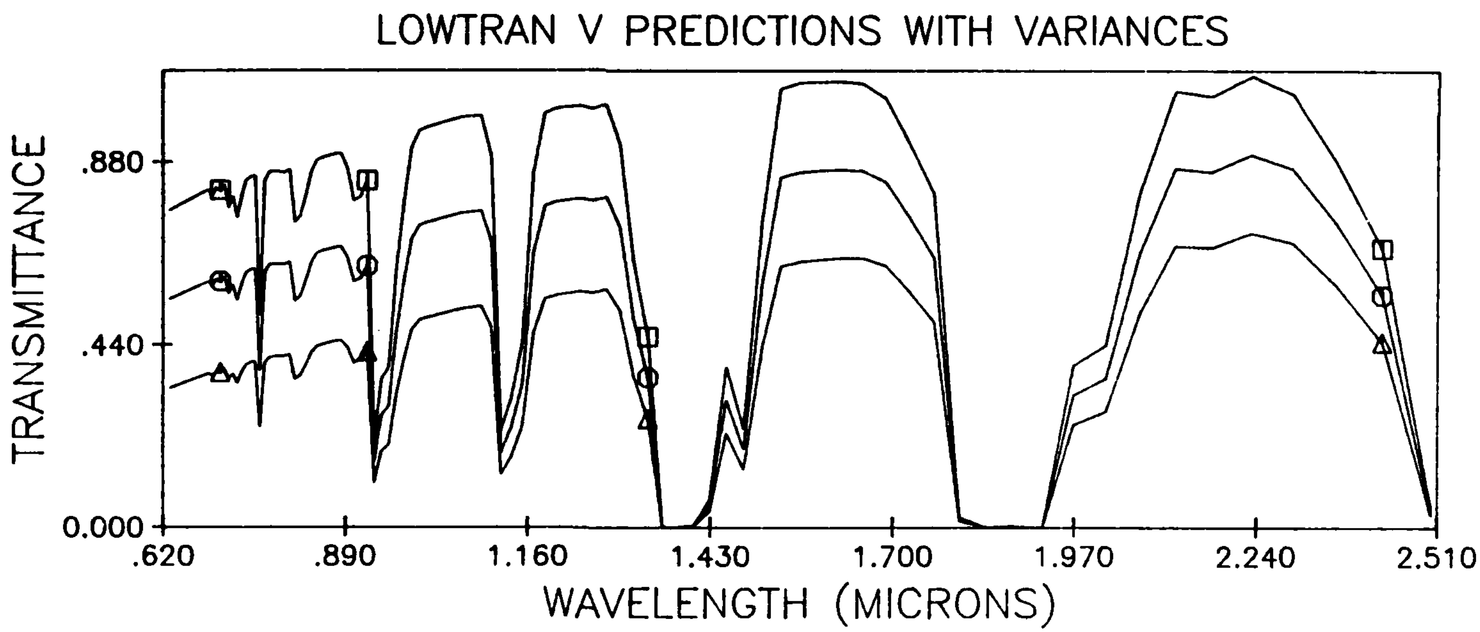

Fig. 1. Plane wave sources; point receivers; horizontal paths.

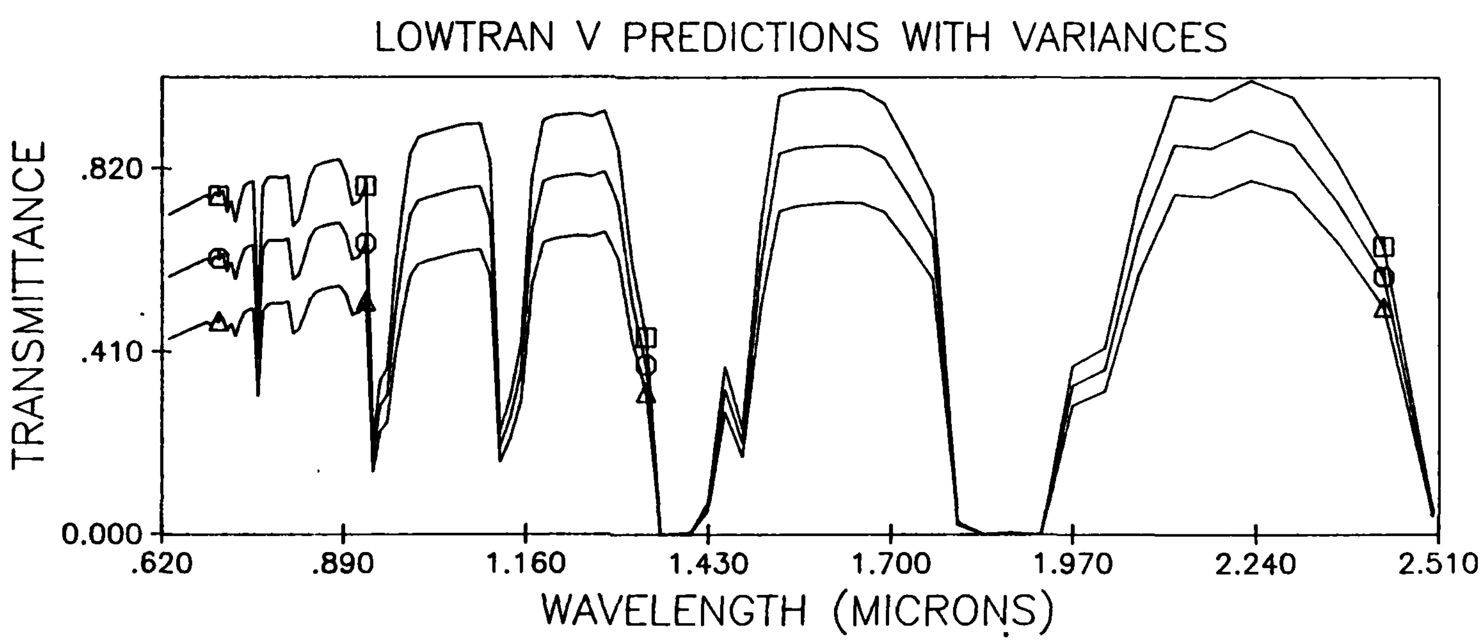

Fig. 2. Plane wave sources; point receivers; upward paths.

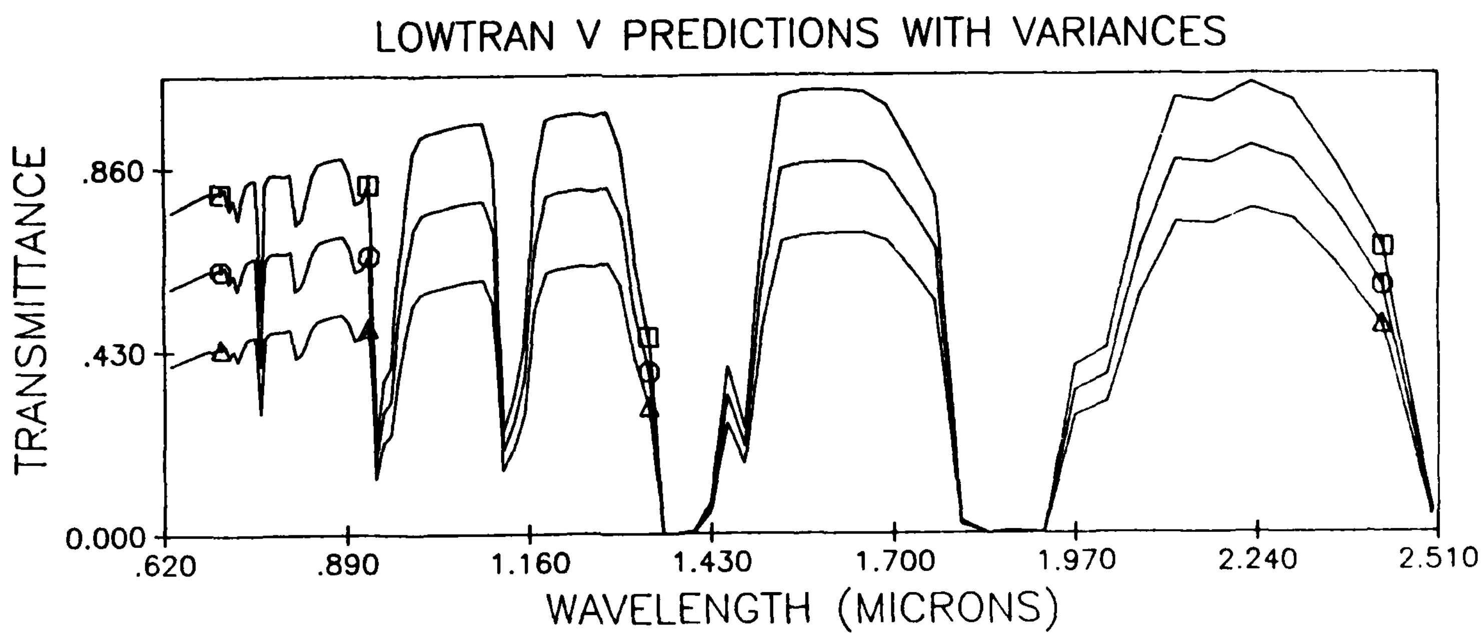

Fig. 3. Plane wave sources; point receivers; downward paths.

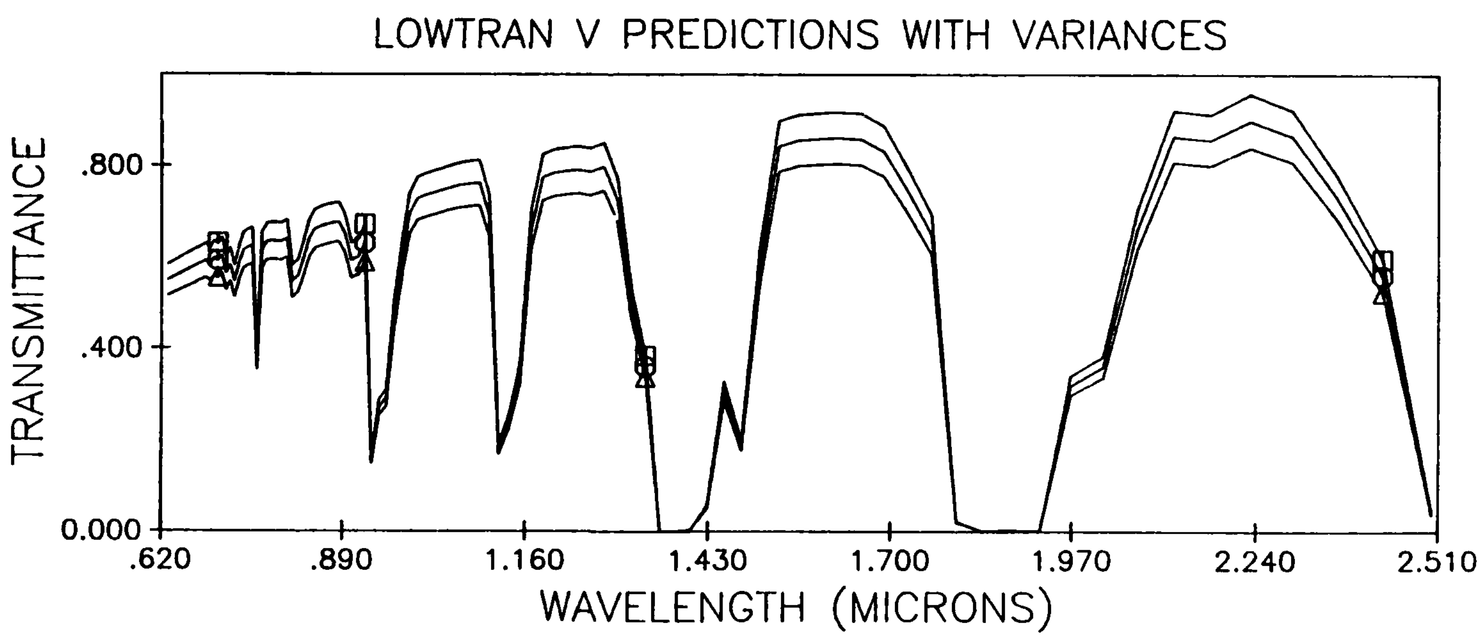

Fig. 4. Plane wave sources; receivers radius R = 10cm; horizontal paths.

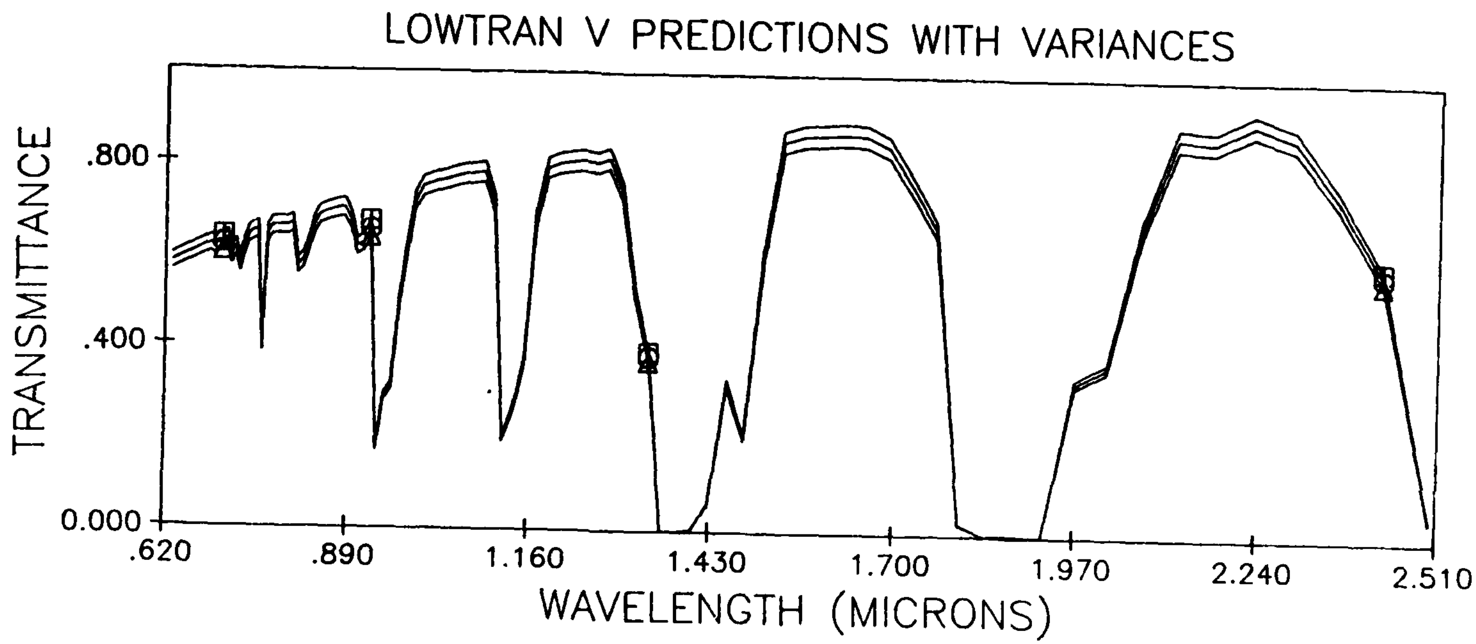

Fig. 5. Plane wave sources; receivers radius R = 10cm; upward paths.

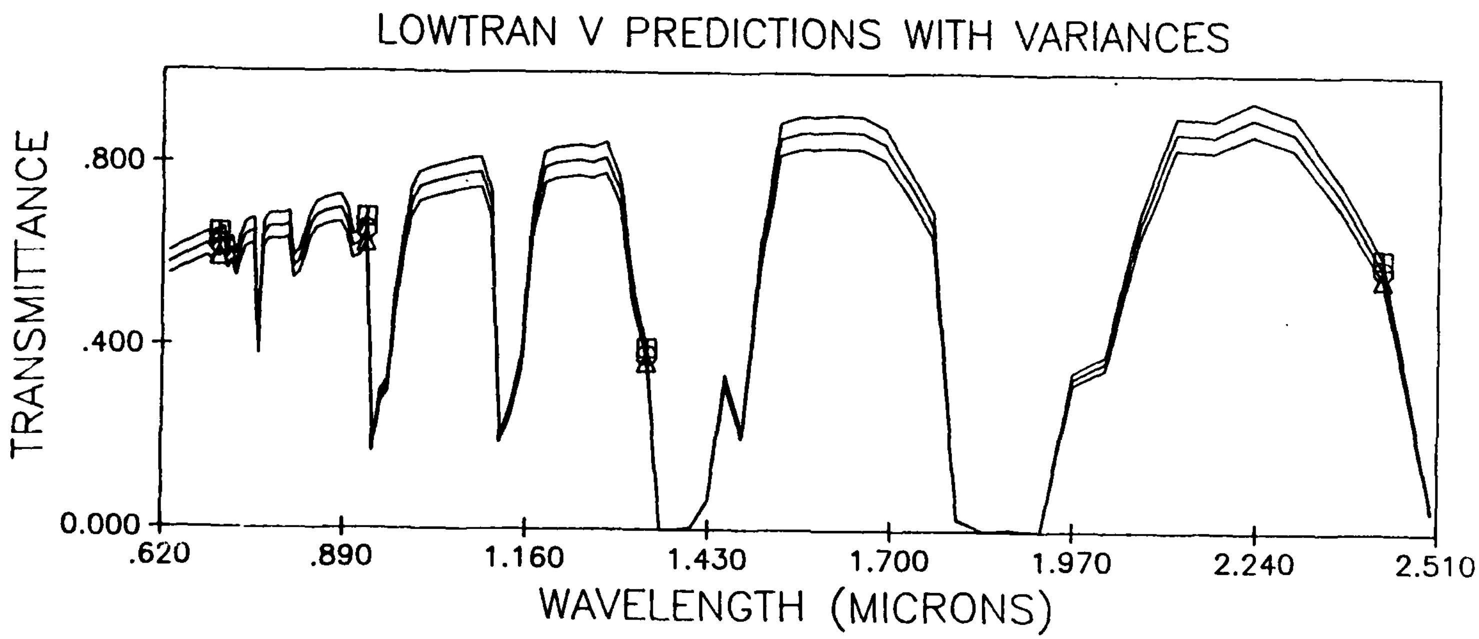

Fig. 6. Plane wave sources; receivers radius R = 10cm; downward paths.

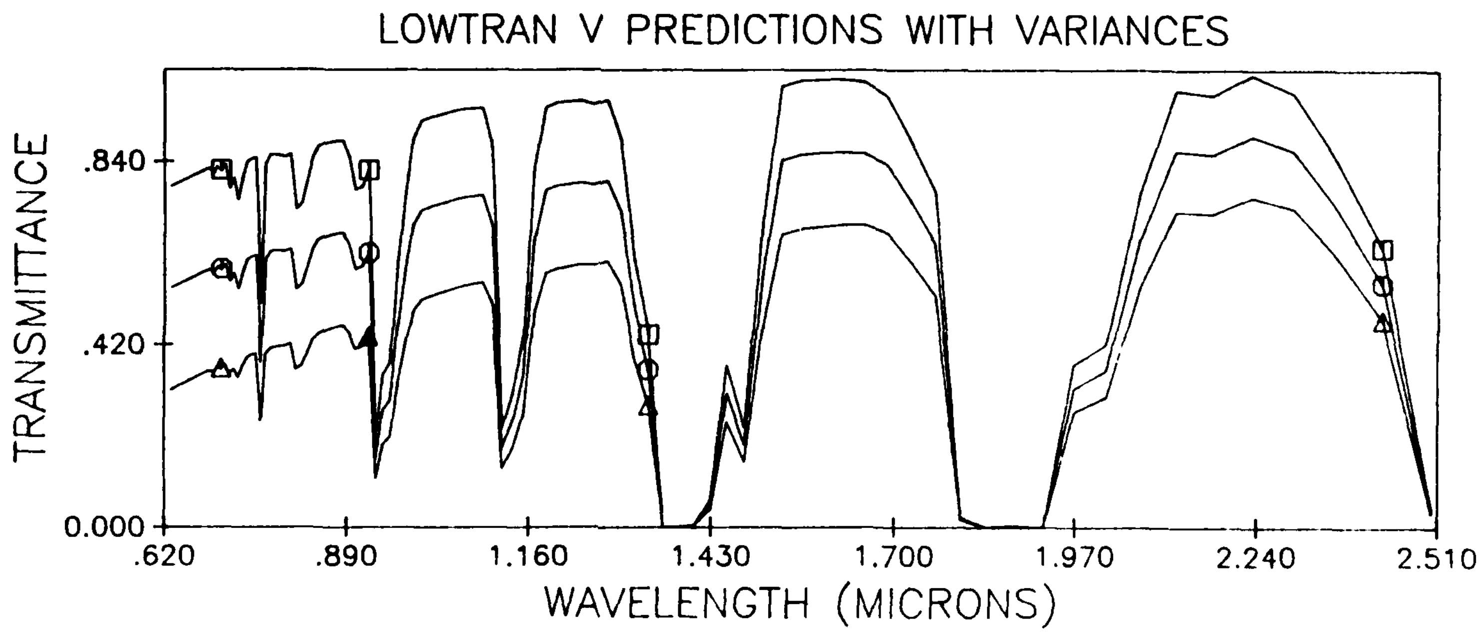

Fig. 7. Beam wave sources, $\alpha_s = 2$cm; point receivers; horizontal paths.

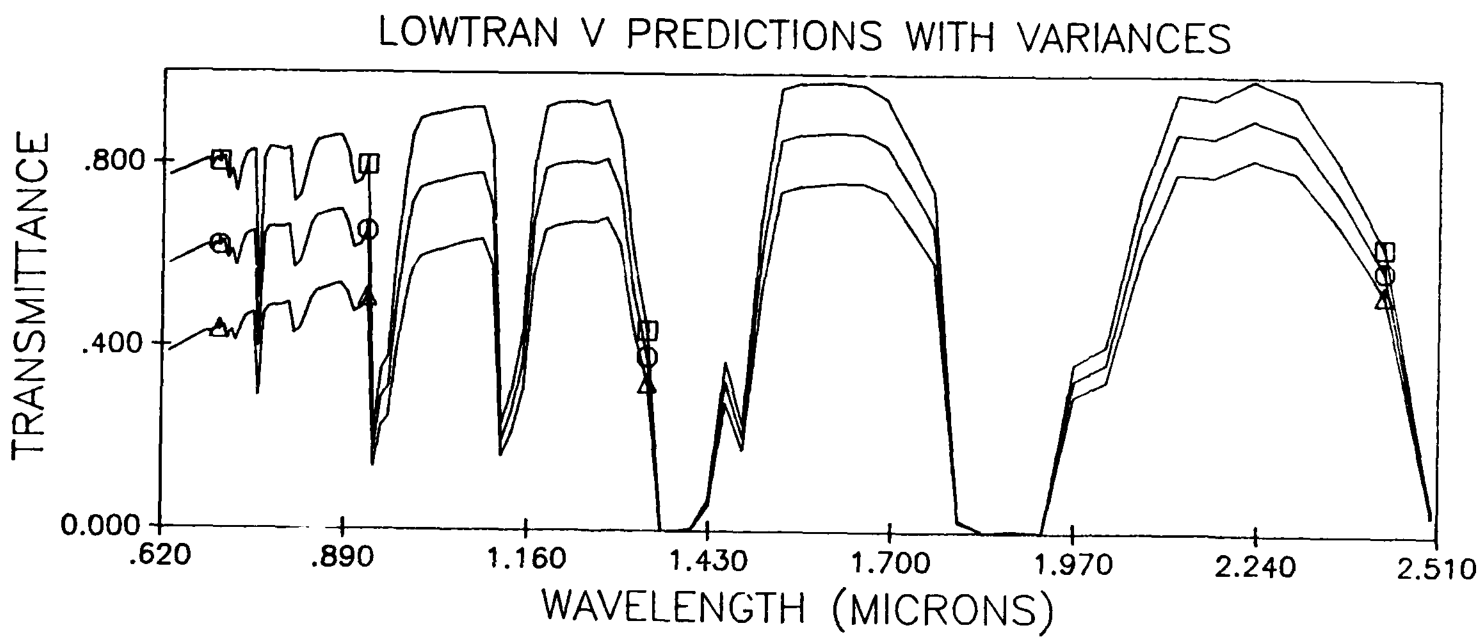

Fig. 8. Beam wave sources, α_s = 2cm; point receivers; upward paths.

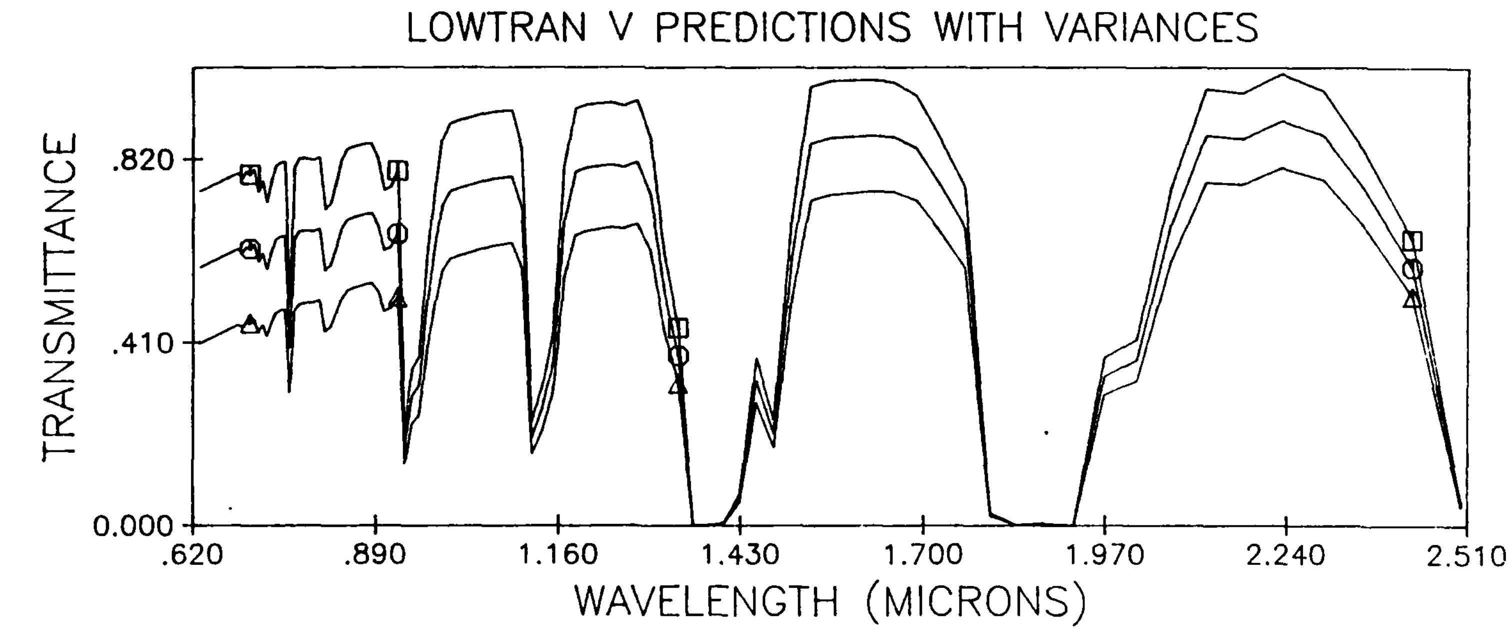

Fig. 9. Beam wave sources, α_s = 2cm; point receivers; downward paths.

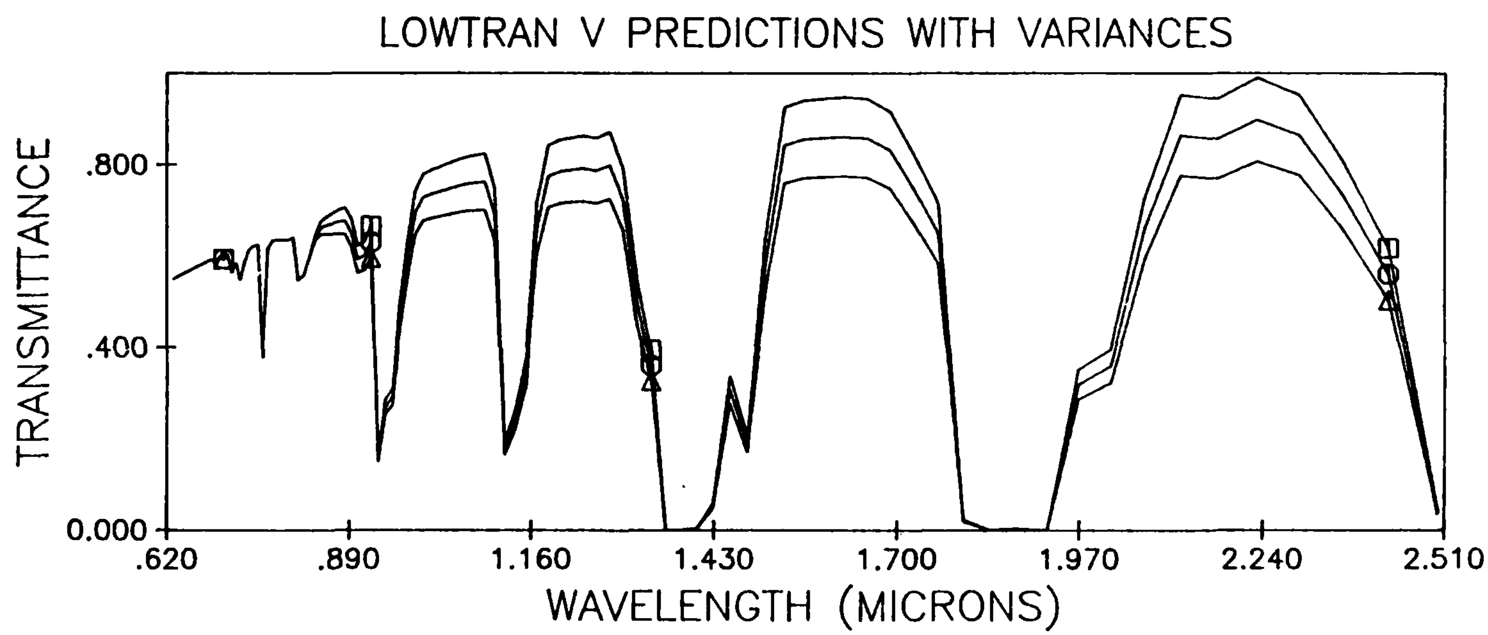

Fig. 10. Beam wave sources, α_s = 2cm; receiver radius R = 10cm; horizontal paths.

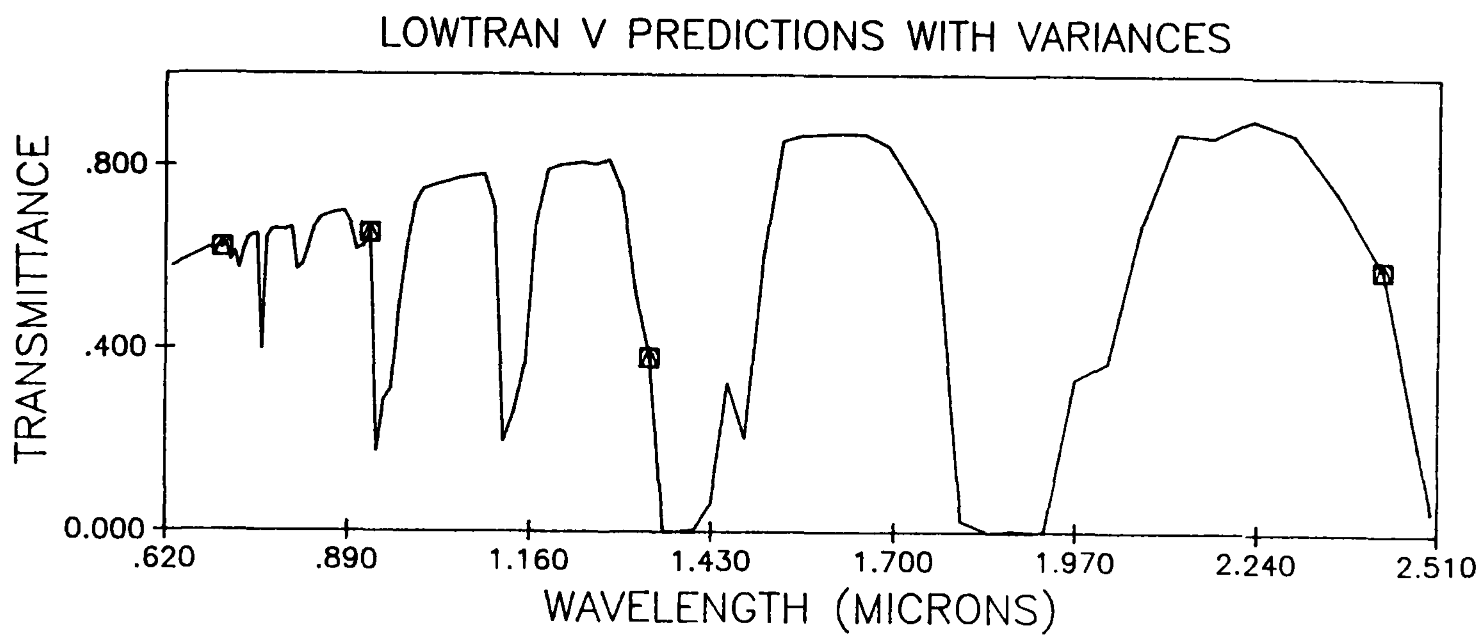

Fig. 11. Beam wave sources, α_s = 2cm; receiver radius R = 10cm; upward paths.

LOWTRAN V PREDICTIONS WITH VARIANCES

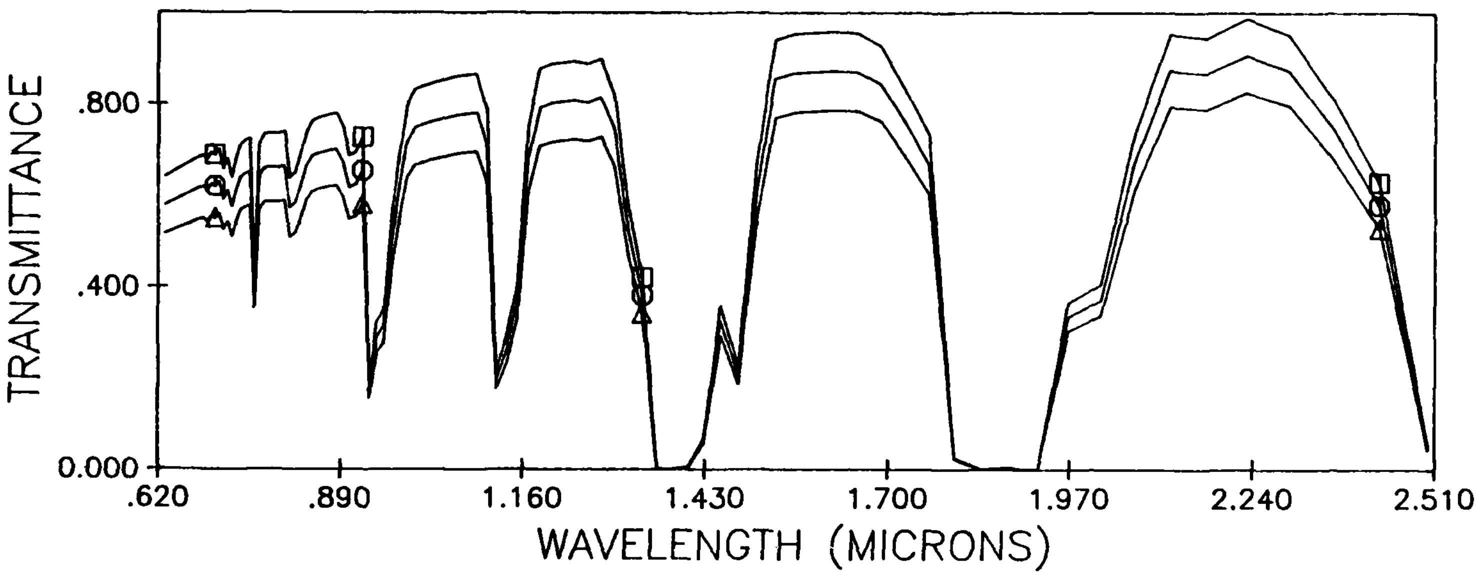

Fig. 12. Beam wave sources, α_s = 2cm; receiver radius R = 10cm; downward paths.

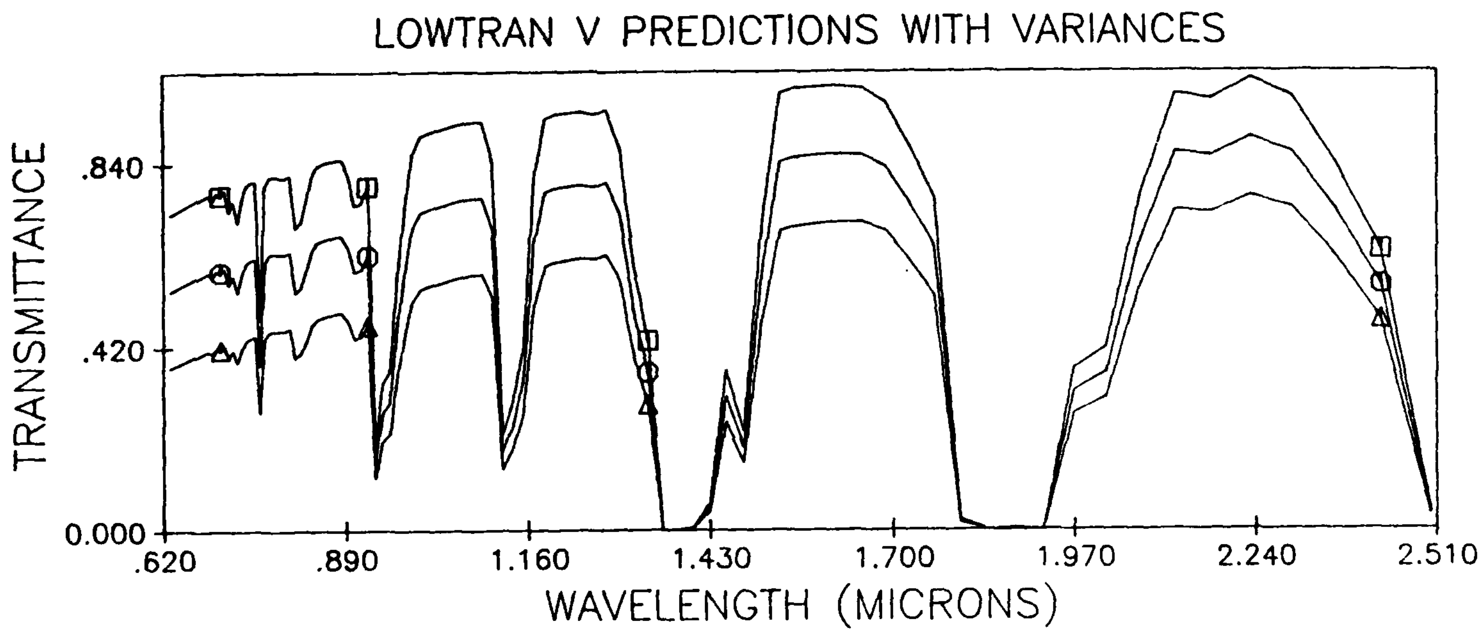

Fig. 13. Spherical wave sources; point receivers; horizontal paths.

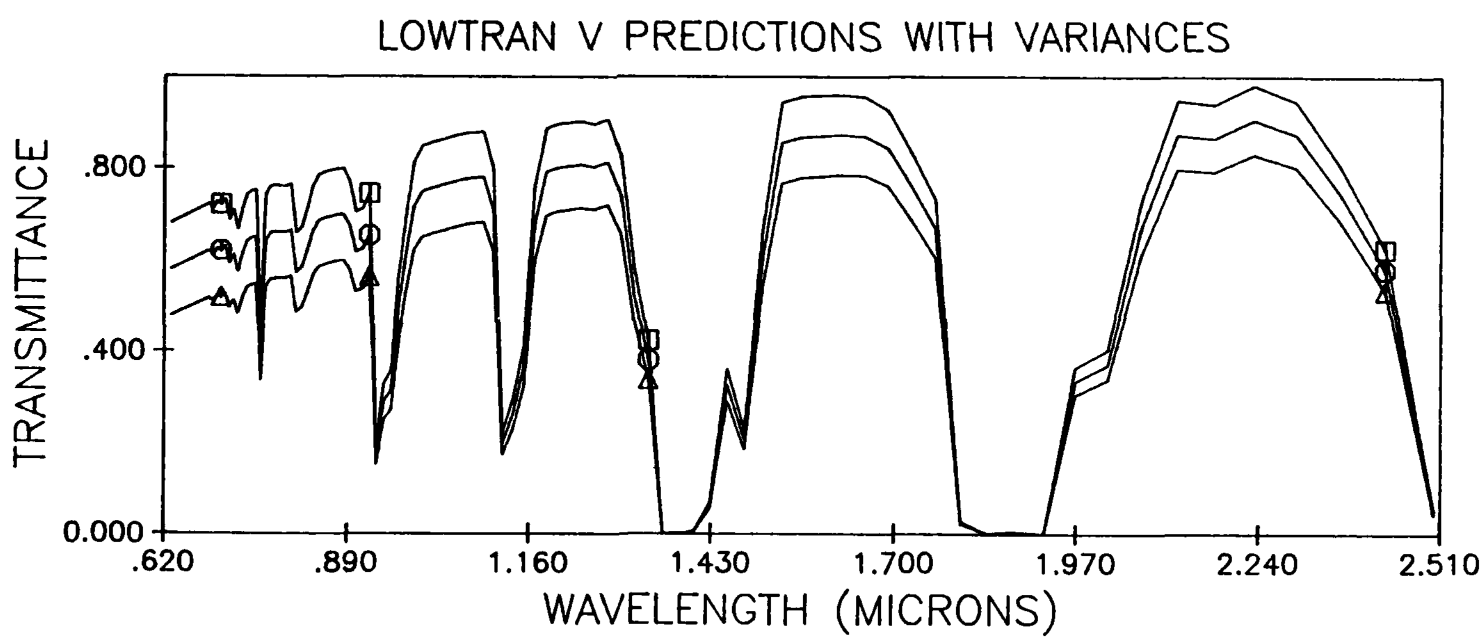

Fig. 14. Spherical wave sources; point receivers; upward paths.

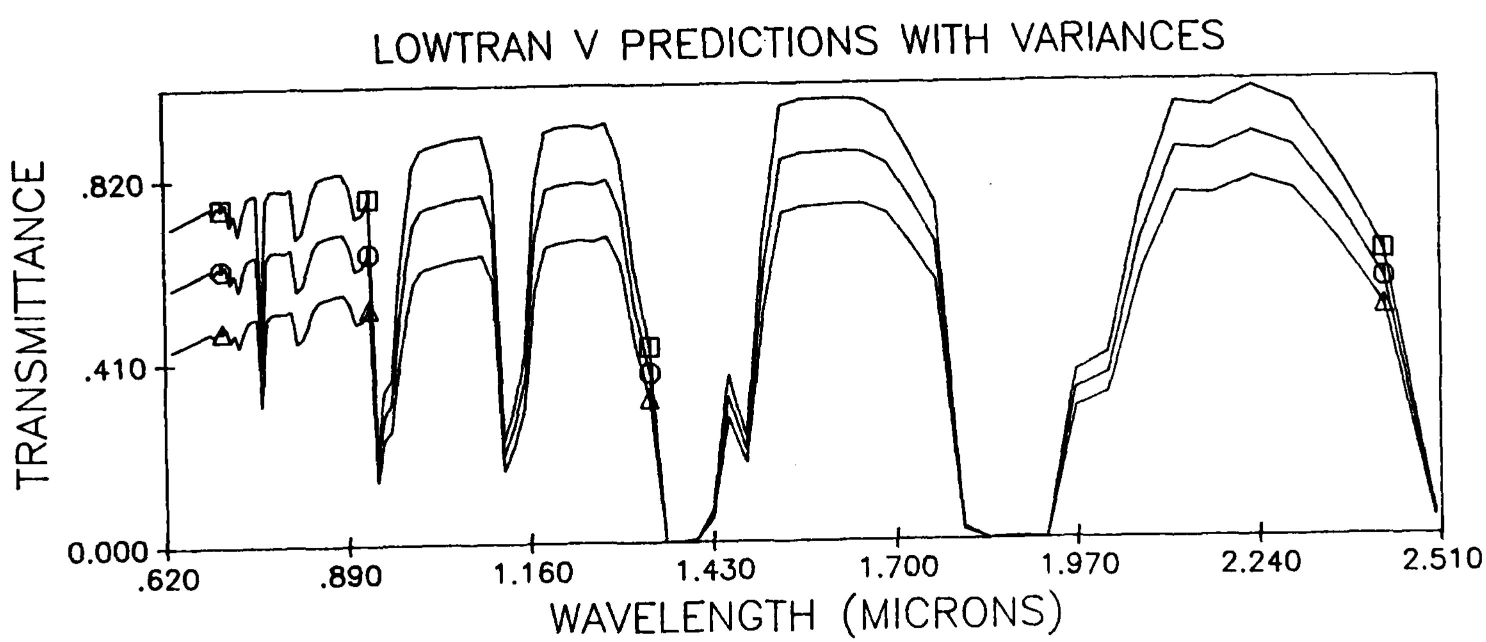

Fig. 15. Spherical wave sources; point receivers; downward paths.

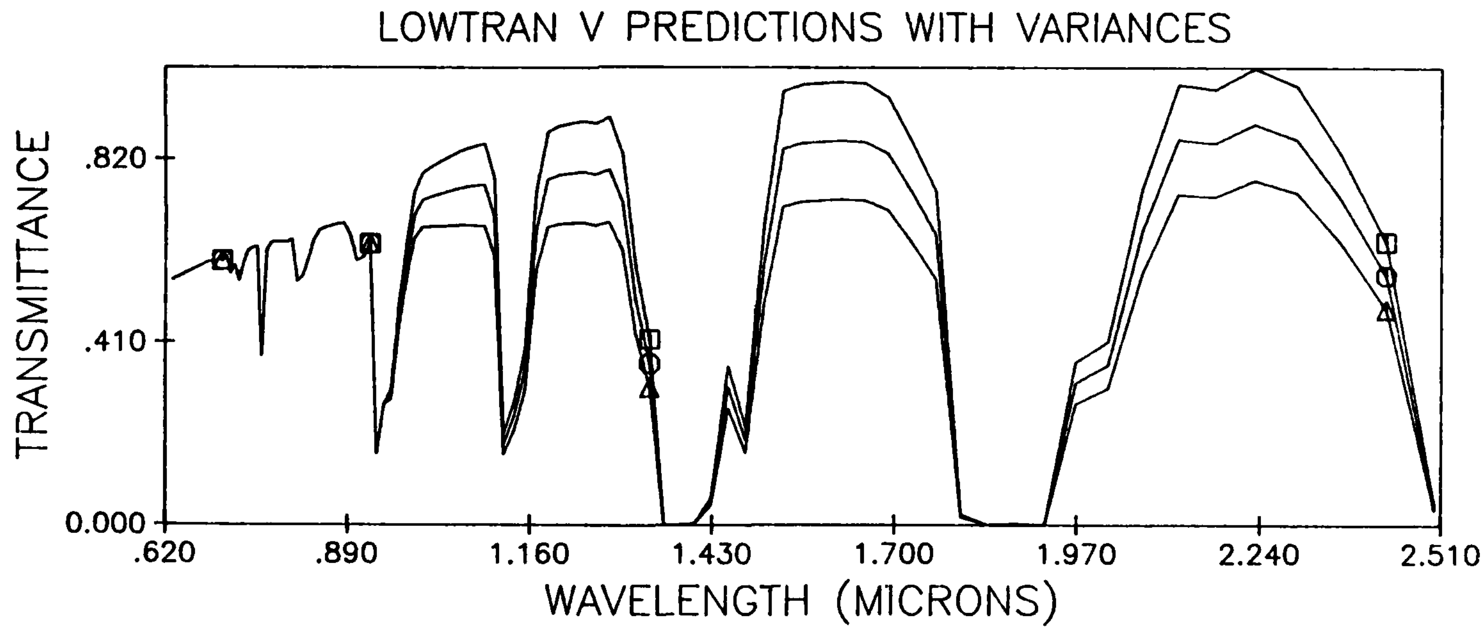

Fig. 16. Spherical wave sources; receivers radius R = 10cm; horizontal paths.

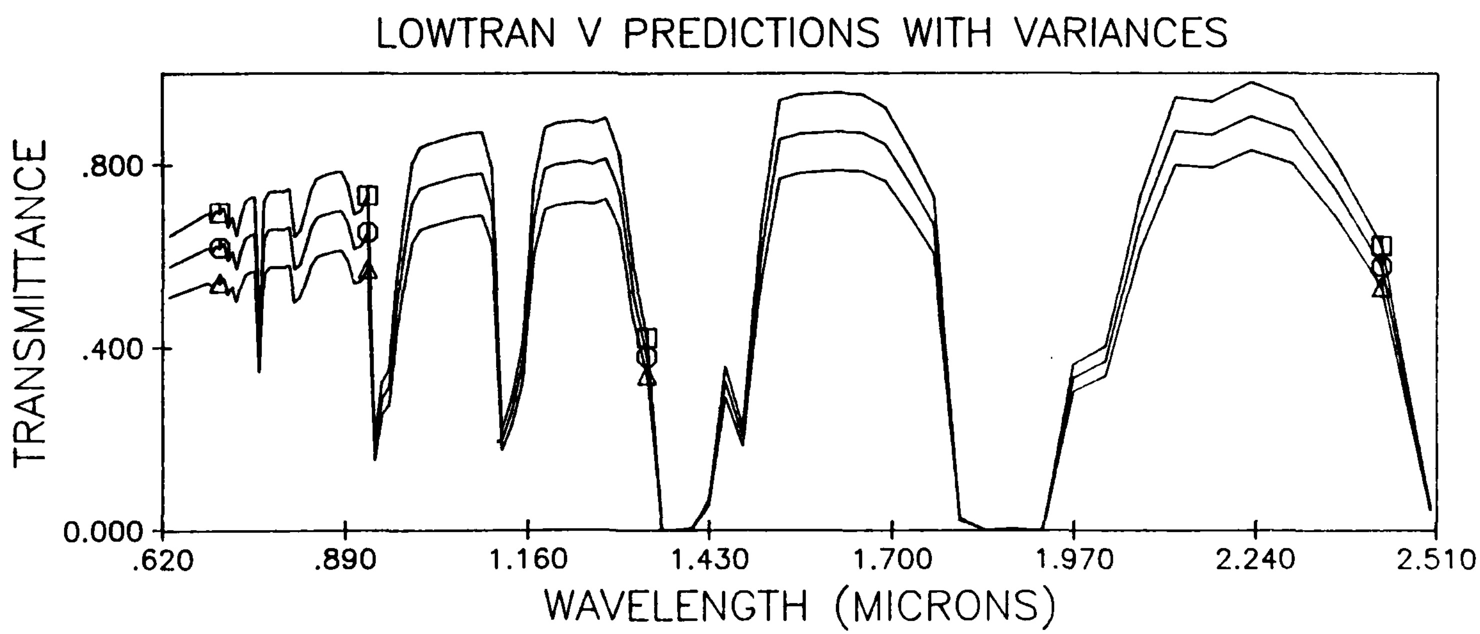

Fig. 17. Spherical wave sources; receicers radius R = 10cm;upward paths.

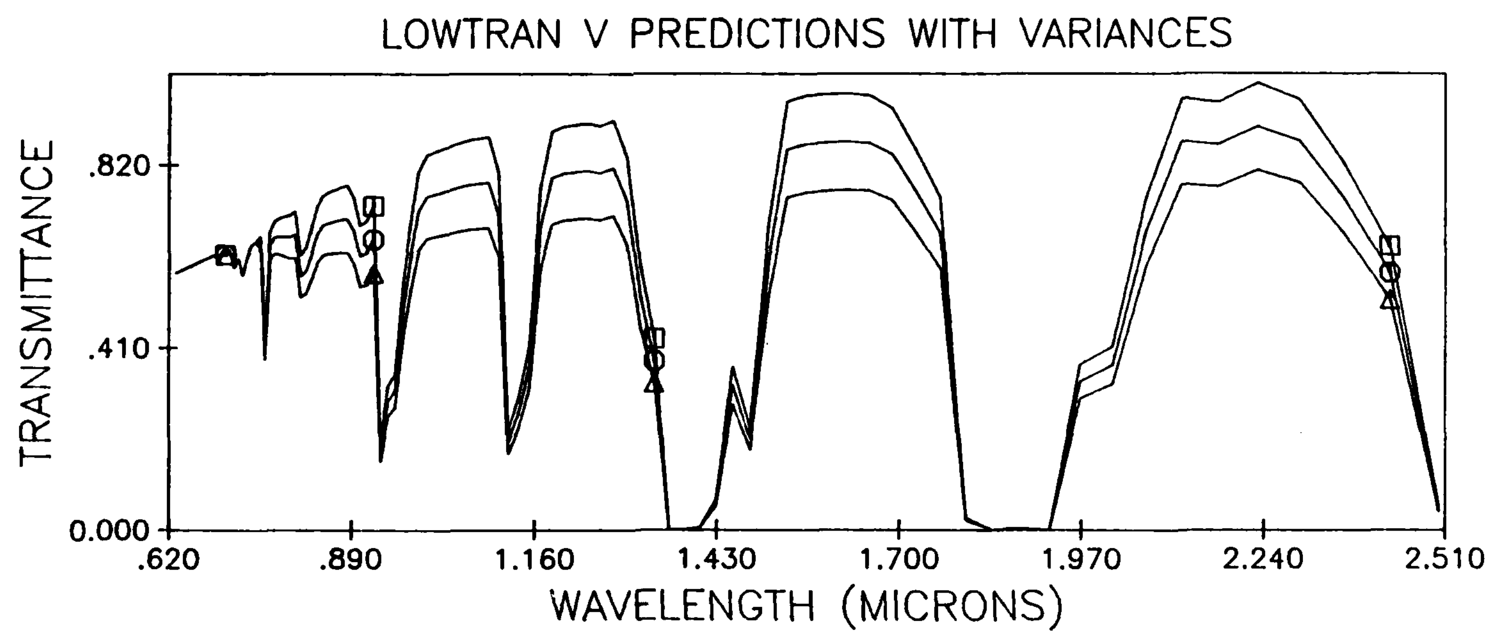

Fig. 18. Spherical wave sources; receivers radius R = 10cm; downward paths.

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